Cold Atom Gyros

Todd L. Gustavson
Director of Advanced Sensor Development
AOSense, Inc.
tgustavson@aosense.com, 408/735-9500 x605

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AOSense

Outline

- Introduction / Applications
- AOSense
- Laser cooled atoms
- Atom interferometry theory
- Cold atom gyro technology progression
- Technology vision

Cold Atom Sensor Applications

- Rotation (Nav., precision pointing, seismic, science)
- Acceleration (Nav., seismic)
- Gravity (Nav., geophysical, basic science)
- Timing (Nav., radar, communication)

Inertial vs GPS

- **GPS limitations**
  - GPS signals may not be available
    - No signal underwater, underground, heavy tree cover
    - Jamming vulnerable
      - Equipment readily available online
  - GPS gives position not orientation
  - Altitude fixes less accurate depending on satellite positions
- **Cold atom inertial sensors**
  - Inertial navigation ("Dead reckoning" – not jammable!)
    - Known starting point
    - Accelerometers for velocity
    - Gyroscopes for orientation
    - Bound position errors while completing mission
  - Common technology base can measure:
    - Time
    - Accelerations & Rotations
    - Gravity and gravity gradients
    - Magnetic fields
  - Air Force Technology Horizons 2010-2030 cites "cold atoms" 26×


200 mW jammer, $40

25 W jammer, $800


Demanding Gyroscope Applications

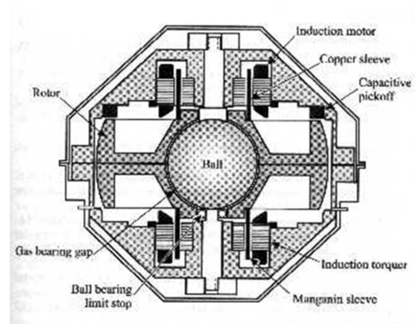
Inertial navigation

Geophysical studies

- Earth rotation rate fluctuations
- Local fluctuations : Seismic, tidal

Tests of General Relativity

- Lense-Thirring
- Geodetic



ESG

G Ring laser

GPB

Atom interferometric navigation solutions

Need	Approach	Impact
Low-cost, ubiquitous, navigation grade IMU (<1 km/h drift)	Compact cluster of atom interferometer gyroscopes and accelerometers (<0.1 L, 1 W)	Autonomous vehicle navigation GPS jammed/denied/multi-path environment
High-accuracy navigation+ grade IMU (<100 m/h drift)	Cluster of atom interferometer gyroscopes and accelerometers	GPS jammed/denied/multi-path environments; Line-of-sight stabilization; Precision attitude determination
Highest accuracy, inertial+ grade IMU (<5 m/h drift)	Atom interferometer sensor cluster Gravity compensation	Highest value military platforms (missile, SSBN); GPS-free precision navigation, gravity map unavailable
Robust, low-cost, gravity gradiometers/gravimeters (drift free, w/ gravity map)	Compact atom interferometer accelerometers	GPS-free precision navigation if gravity map available

Some gyroscope figures of merit

Sensitivity ARW	deg/hr$^{1/2}$
Bias offset/ stability	deg/hr
Scale factor stability	ppm
Acceleration sensitivity	deg/hr/g
Input axis misalignment	deg

. . . others depending on application

AI gyro characteristics

- Bias instability: <10 μdeg/h
- Noise (ARW): <10 μdeg/h$^{1/2}$
- Scale factor: <5 ppm

Source: Proc. IEEE/Workshop on Autonomous Underwater Vehicles

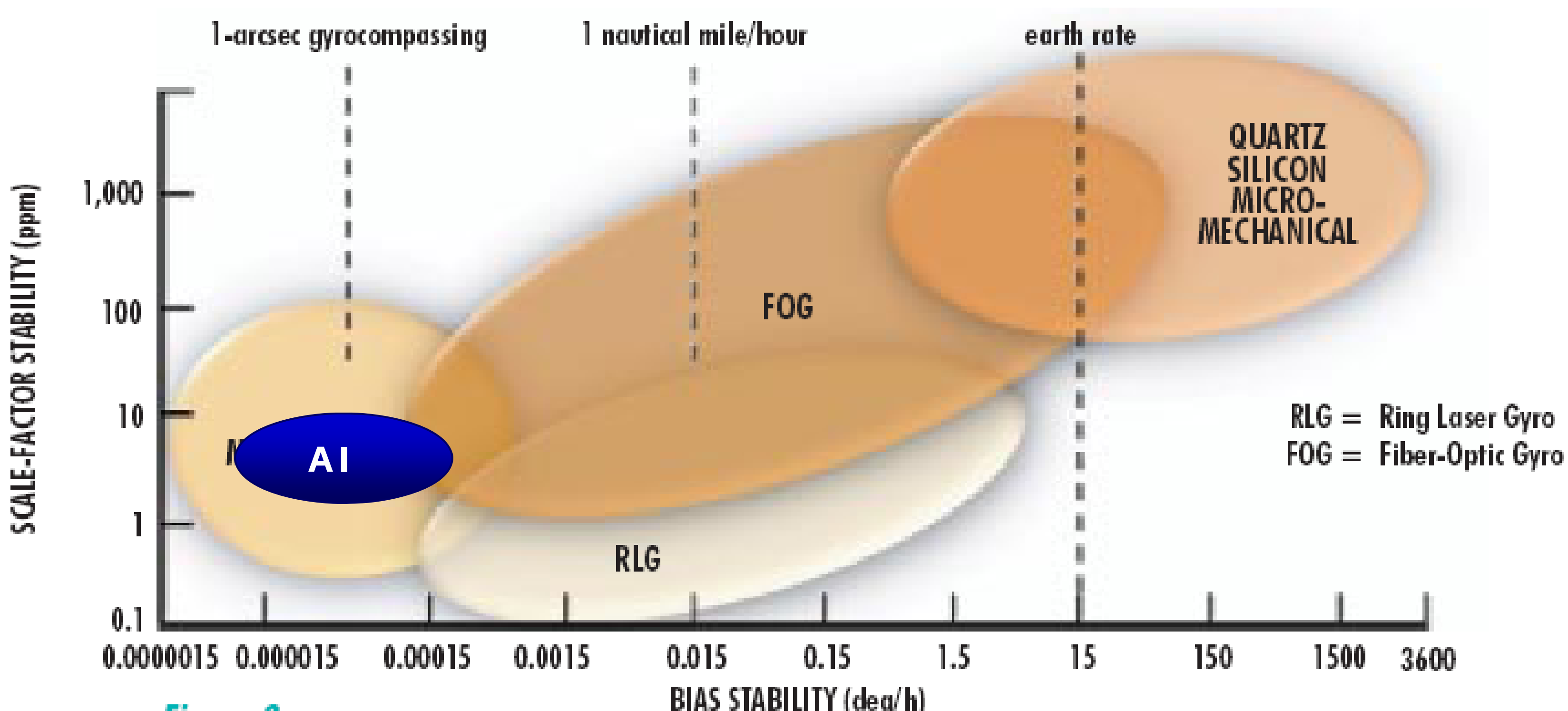
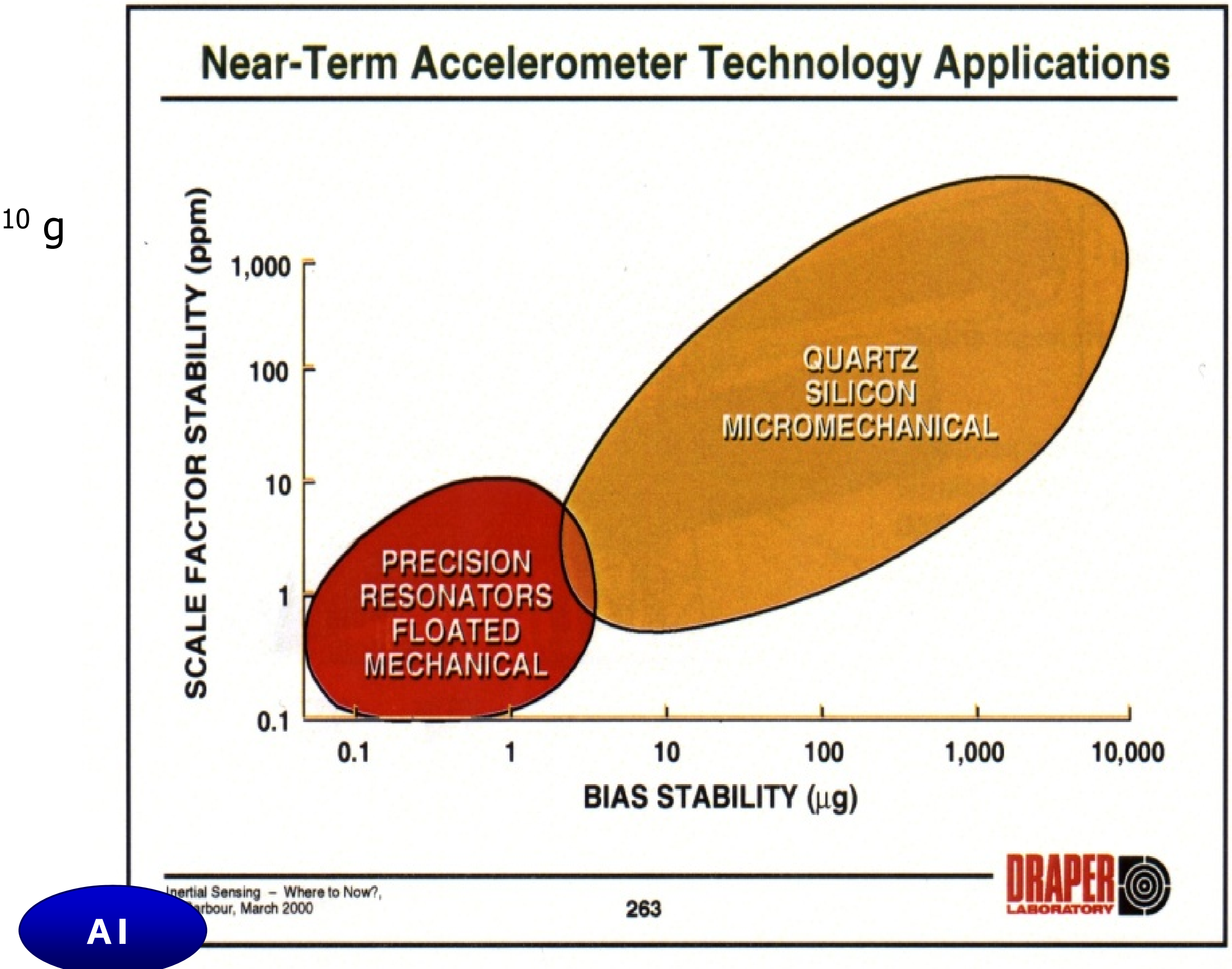


Figure 8

AI accelerometer characteristics

- Bias instability: $<10^{-10}$ g
- Noise: $<10^{-9}$ g/Hz$^{1/2}$
- Scale factor: 10^{-10}

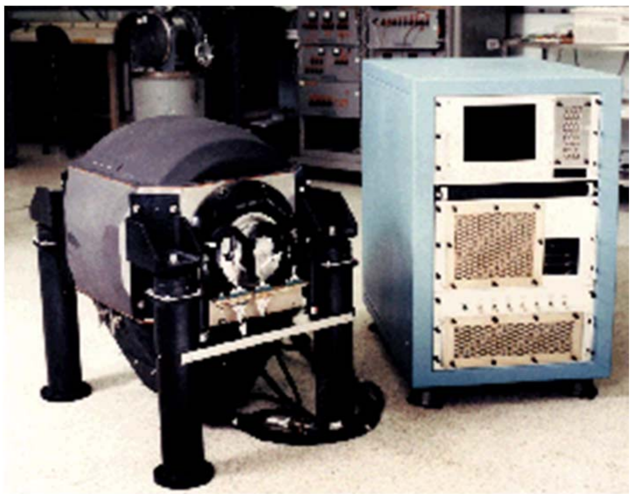


Source: Proc. IEEE/Workshop on Autonomous Underwater Vehicles

Airborne Gravity Gradiometer

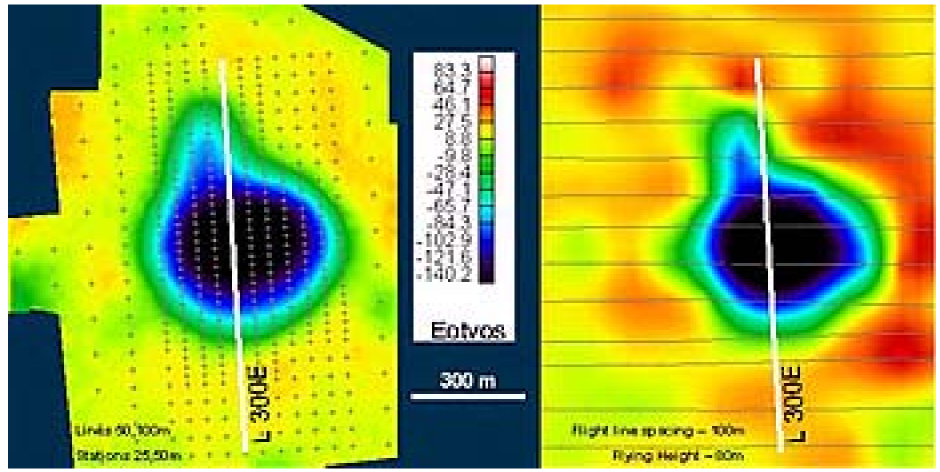
Existing technology

Sanders Geophysics



LM Niagra Instrument

Land: 3 wks. Air: 3 min.

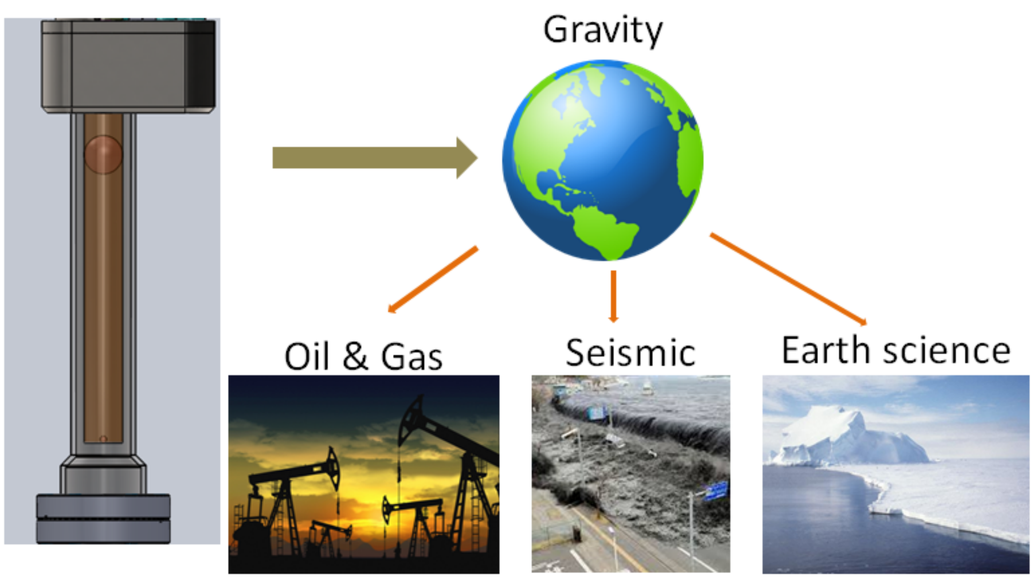


Kimberlite pipe (diamonds)

AI sensors potentially offer 10× – 100× improvement in detection sensitivity at reduced instrument costs.

Gravimeter (NSF SBIR)

- Oil and gas service industry needs reliable, robust, field deployable gravity sensors for providing short- and long-term gravity survey data to the oil, gas, and mineral extraction industry.
- Existing gravimeters suffer from lack of robustness, high power consumption, relatively high cost, substantial drift rates, accuracy and sensitivity limits, and long survey times.



Miro Shverdin <mshverdin@aosense.com>

AOSense, Inc.

- Founded in 2004 to develop cold-atom sensors
  Brent Young CEO
- Core capability is design, fabrication and testing of sensors based on cold-atom technologies.
- Staff of 39
- 20k sq. ft. R&D space (clean rooms, assembly, testing)

AOSense, Inc.
767 N Mary Ave.
Sunnyvale, CA 94085
(408) 735-9500
www.aosense.com

AOSense Executive Team

James Spilker, Jr., Executive Chairman

- Consulting Prof. EE and Aero/Astro, Stanford
- Co-founder, Chairman and CEO, Stanford Telecom
- Invented delay lock loop tracking technique for CDMA; GPS co-architect
- Co-edited *GPS, Theory and Applications* (AIAA, 1996)
- Defense Science Board
- Air Force Independent Review Team for GPS

Brent Young, CEO

- 20 y experience designing, building and testing precision atomic sensors at NIST, JPL, Stanford and Yale
- Developed stable laser: $\sigma_y(1\ \text{s}) = 3\times10^{-16}$ and $\Delta\nu_{FWHM}(32\ \text{s}) = 0.6$ Hz

Mark Kasevich - Chief Scientist (Consulting)

- Prof. Physics and Applied Physics, Stanford
- Demonstration of first cold-atom clock, gravimeter, gyroscope and gravity gradiometer
- PI DARPA PINS (Phase I, II) program to develop cold-atom navigation systems
- PI NGA MAGGPI program to develop mobile gravity gradient sensors
- PI SP-24/Trident program to develop high-accuracy navigation sensors

Leo Hollberg – CTO (Consulting)

- 30 y experience in atomic physics at CU-Boulder, Bell Labs and NIST
- Group leader in Time & Frequency Division at NIST
- Demonstrated first 3D optical molasses, squeezed light, lasing w/o inversion, cold Ca and Yb optical clocks w/ fs comb
- Contributed to cesium primary frequency standards, PARCS, CSAC, chip-scale magnetometers and gyroscopes
- Awards: Dept. of Commerce Gold and Silver Medals; I.I. Rabi; and Meggers

AOSense staff contributions to AI inertial R&D

1984 First proposal for light-pulse AI
B. Dubestky, A. P. Kazantsev, V. P. Chebotayev, V. P. Yakovlev, JETP Lett. 39, 649 -51 (1984).

1985 Laser cooling
S. Chu, L. Hollberg, J. E. Bjorkholm, A. Cable, A. Ashkin, Phys. Rev. Lett. 55, 48 (1985).

1989 Atomic fountain
M. A. Kasevich, Erling Riis, Steven Chu, Ralph G. DeVoe Phys. Rev. Lett. 63, 612–615 (1989).

1991 Light pulse atom interferometer
M. A. Kasevich and S. Chu, Phys. Rev. Lett. 67, 181–184 (1991).

1991 Diode lasers for atomic physics
C. E. Wieman and L. Hollberg, Rev. Sci. Instrum. 61, 1 (1991).

1992 AI gravimeter/accelerometer
M. Kasevich and S. Chu, Appl. Phys. B, 54, 321 (1992).

1995 Bose-Einstein Condensation
Anderson, M. H.; Ensher, J. R.; Matthews, M. R.; Wieman, C. E.; Cornell, E. A., Science, 269, 198-201 (1995).

1997 AI gyroscope
T. Gustavson, P. Bouyer, and M. Kasevich, Phys. Rev. Lett. 78, 2046–2049 (1997).

1998 AI gravity gradiometer
M. J. Snadden, J. M. McGuirk, P. Bouyer, K. G. Haritos, and M. A. Kasevich, Phys. Rev. Lett. 81, 97 (1998).

1998 Guided BEC gravimeter
B. Anderson and M.A. Kasevich, Science, 282, 1686 (1998).

2000 High sensitivity gyroscope
T. L. Gustavson, A. Landragin, M. A. Kasevich, Class. Quantum Grav. 17, 2385 (2000).

2002 High accuracy AI gravity gradiometer
J. M. McGuirk, G. T. Foster, J. B. Fixler, M. J. Snadden, and M. A. Kasevich, Phys. Rev. A 65, 033608 (2002).

2006 High accuracy gyroscope
D. Durfee, Y. Shaham, and M. A. Kasevich, Phys. Rev. Lett. 97, 240801 (2006).

2008 Moving platform gravity gradiometer
M.A. Kasevich, MAGGPI program final report, DTIC, 2008.

Capabilities

Navigation Engineering
Atomic Physics
Optical Physics
Optical Engineering
Opto-Mechanical Engineering
Electrical Engineering
Embedded Systems
Software Engineering
Vacuum Engineering
Mechanical Engineering
Packaging
Precision Manufacturing

Laser-cooled atoms

Atomic physics – tools of the trade

- Source: heat alkali metal -> vapor
- Trap atoms from a dilute vapor (1 billion/s)
- Cool atoms to few μK (slow from speed of jet plane to mosquito)
- Count atoms in a particular quantum state (resonant fluorescence)
- Transfer atoms between different internal states
  - 100% transfer = mirror
  - 50% transfer = beam splitter
- Accelerate (launch) atoms: 1000 g
- Lock lasers to atomic transition
- Interferometry

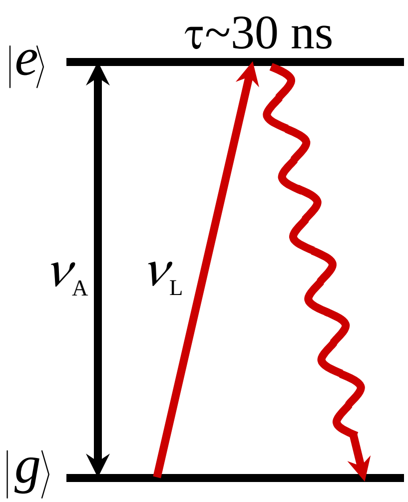
1997 Nobel Prize in Physics awarded to Chu, Cohen-Tannoudji and Phillips for laser cooling and atom manipulation techniques

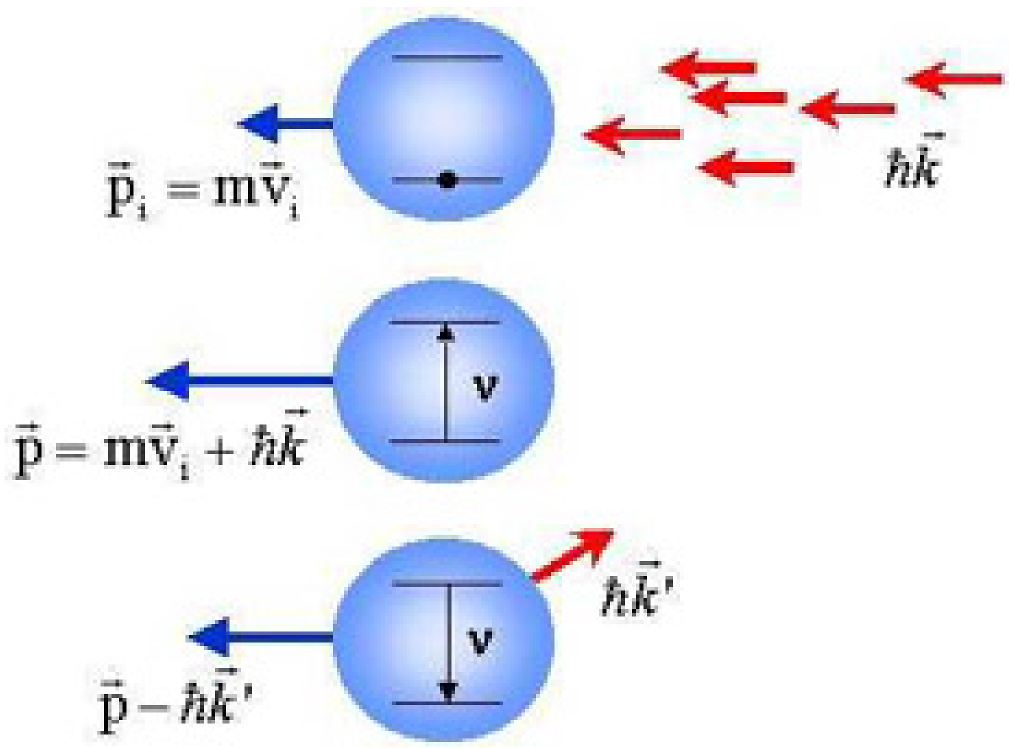
Image source: www.nobel.se/physics

Incoherent scattering

v ~100 m/s at T = 25 °C

2-level atom

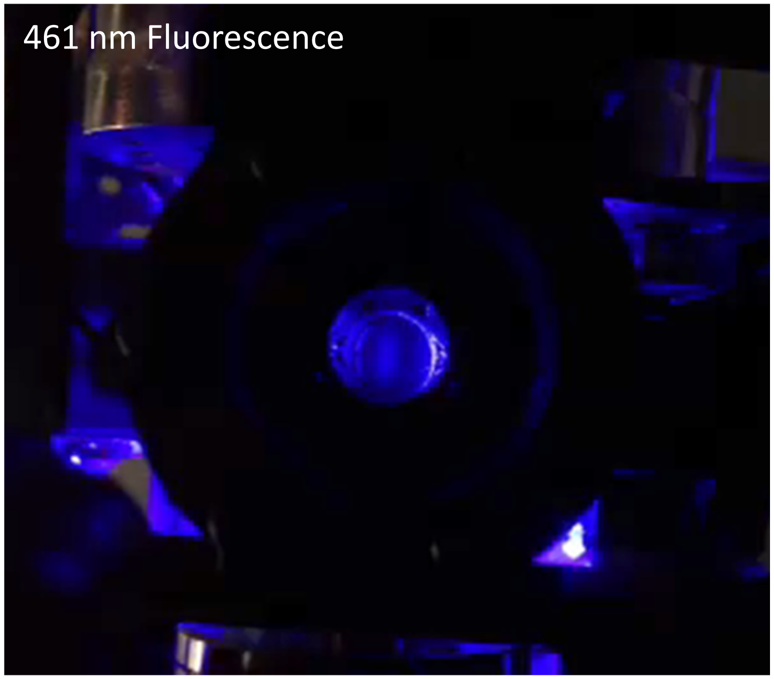




$\Delta v = \hbar k/m$ ~1 cm/s

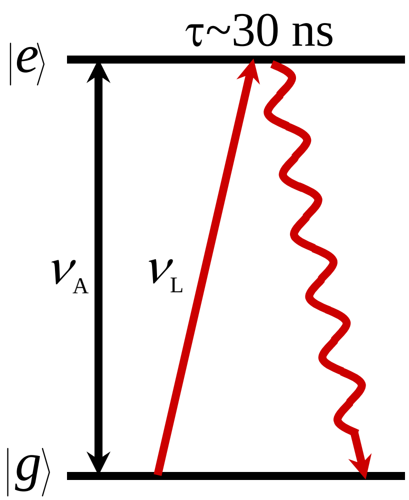
Fluorescence

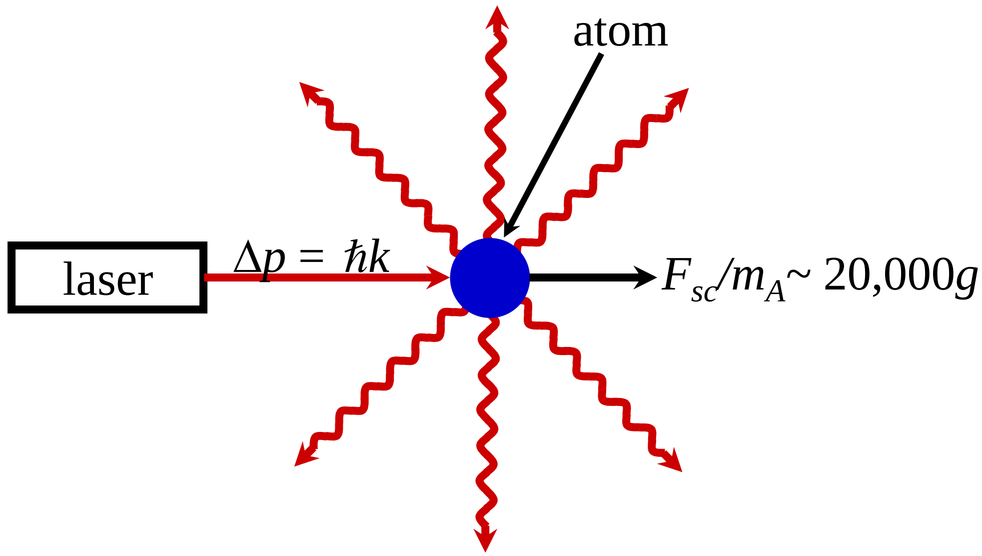
Strontium atomic beam



Spontaneous light force

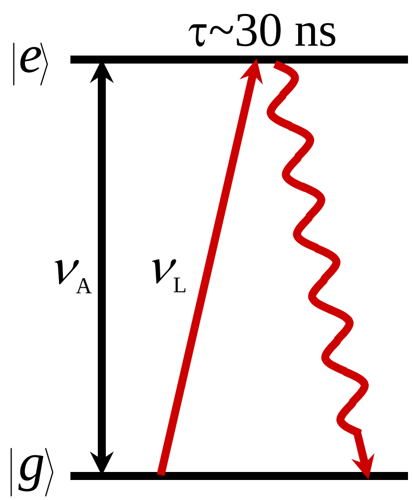
2-level atom

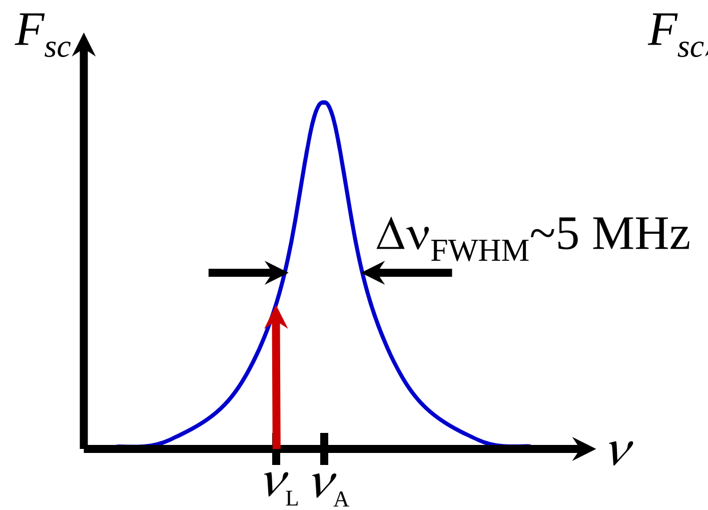


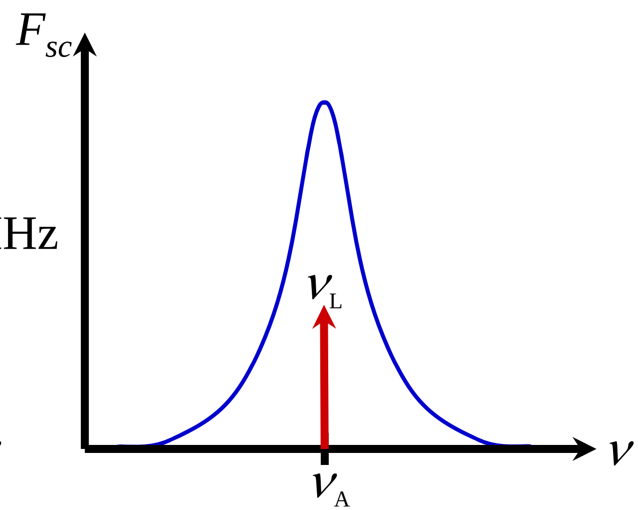


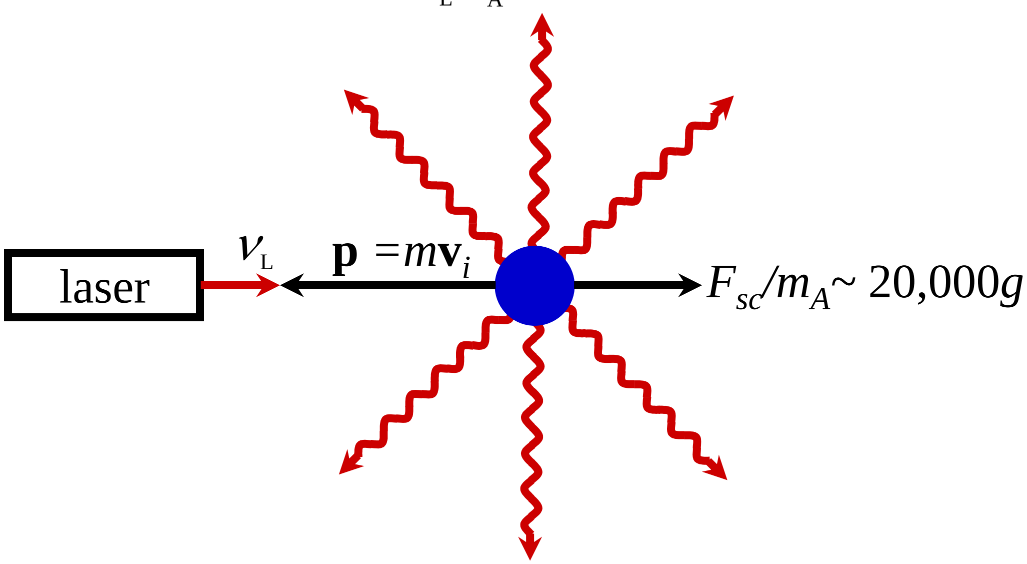
Laser slowing

2-level atom



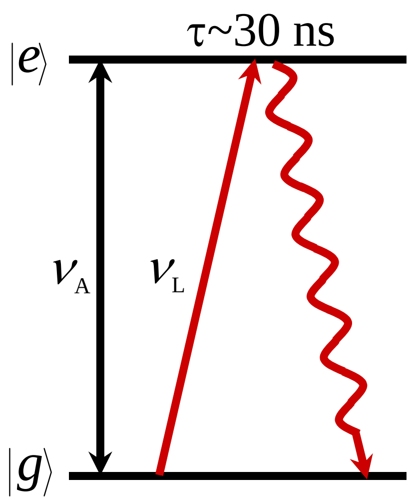




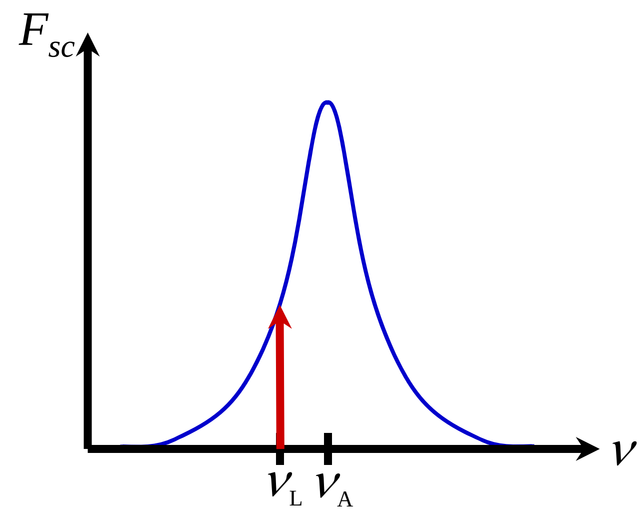


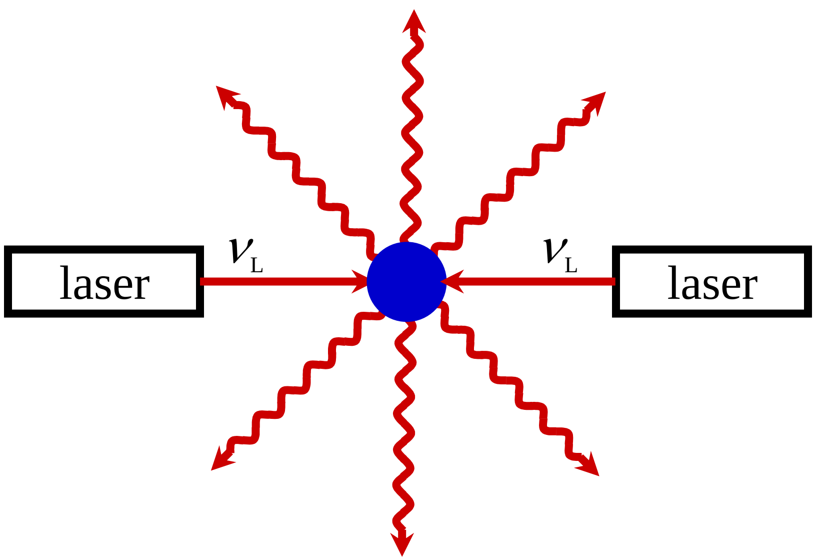
Doppler cooling

2-level atom



lab frame





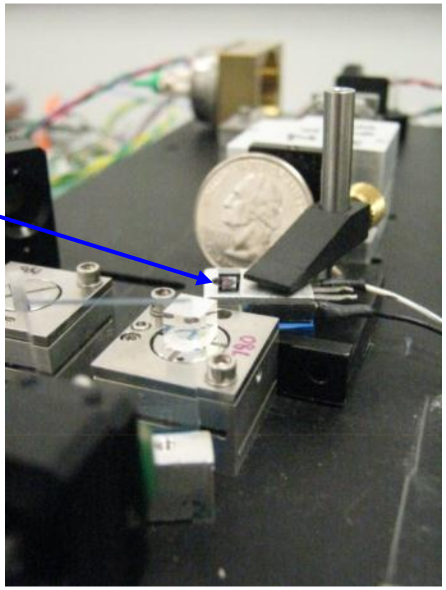
Laser lock

Laser frequency stabilization with immunity to platform dynamics

Key features:

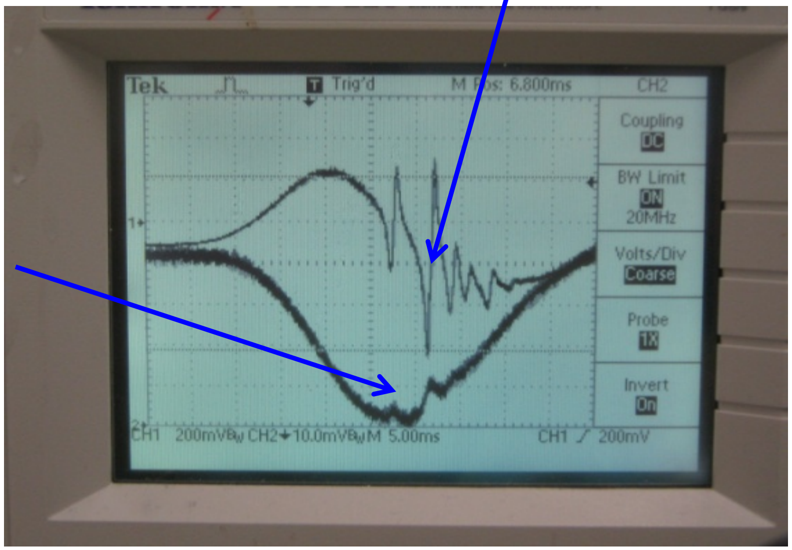
- DFB laser locked to ^{87}Rb transition
  - DFB/DBR provides rugged diode laser solution for AO sensors
  - Saturated absorption spectroscopy of Rb vapor provides Doppler-free lock signal
  - Thermal atom velocity (~300 m/s) used in lock dominates compared to platform dynamics
- FM spectroscopy @ 20 MHz
  - FM enables lock detection far outside of vibration frequency range, decouples DC fluctuations
- AOSense lock electronics provide ~1 MHz servo BW
  - Servo response time much faster than acceleration timescale
  - Very large servo gain near DC

NIST
MEMS-Rb cell



lock signal

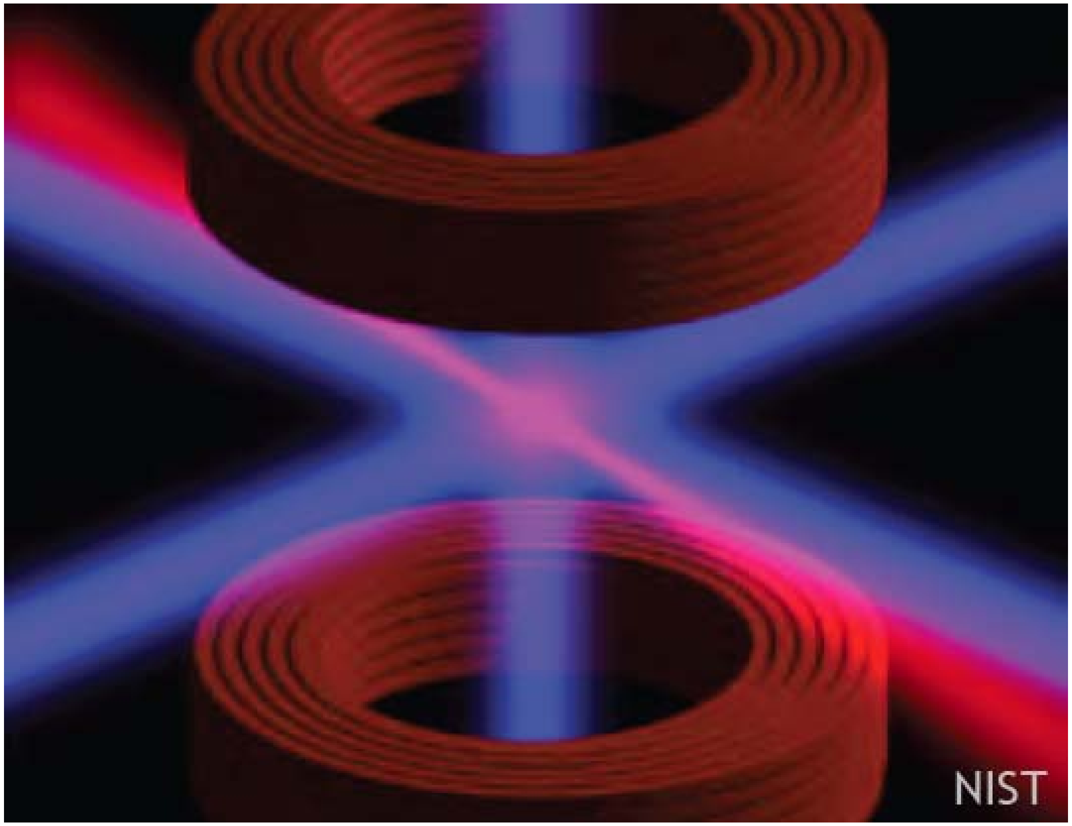
Rb
absorption



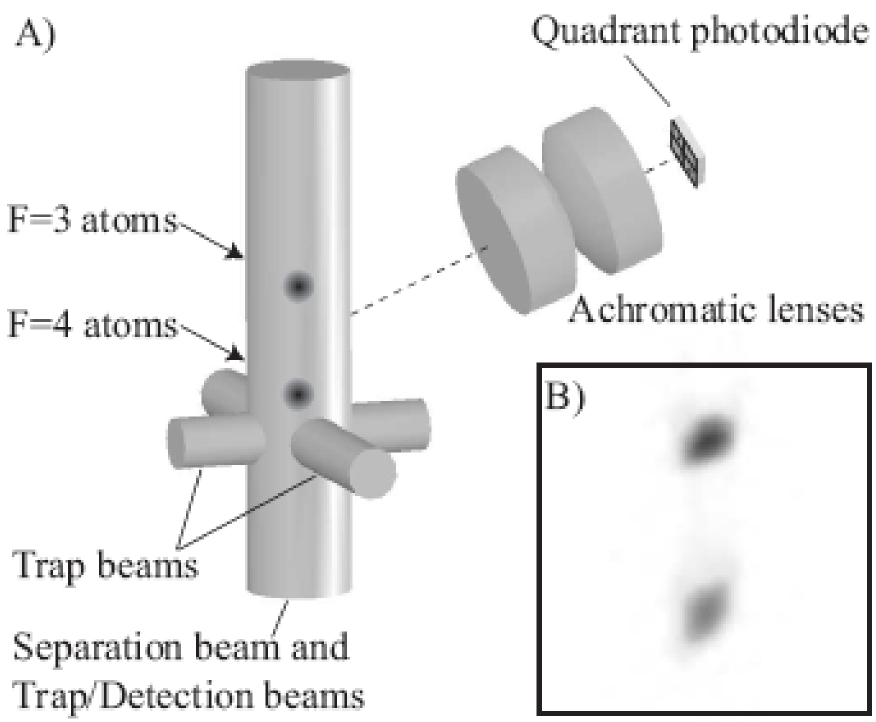
3D Magneto-optic trap (3D-MOT)

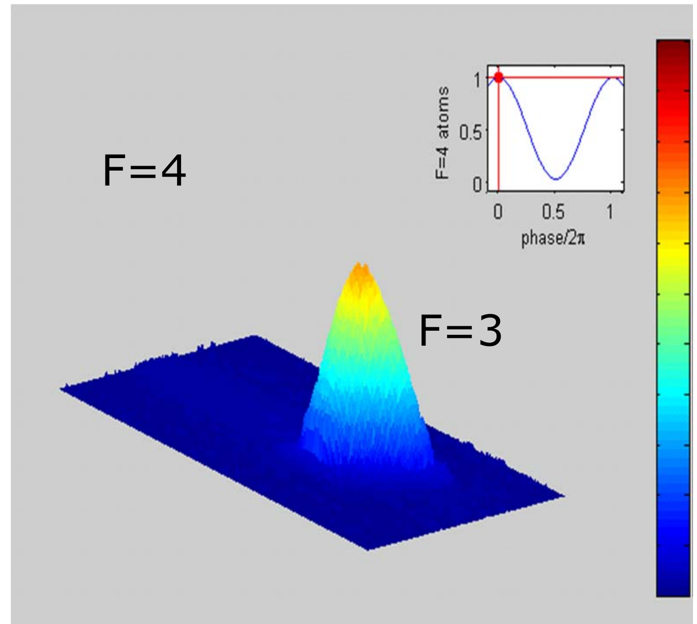
- Typical parameters
  - N ~10^9 atoms/s loading
  - Temperature after polarization gradient cooling ~few μK

Laser cooling/atom manipulation techniques are used to achieve the required velocity control for the atom sources.



Normalized fluorescence detection



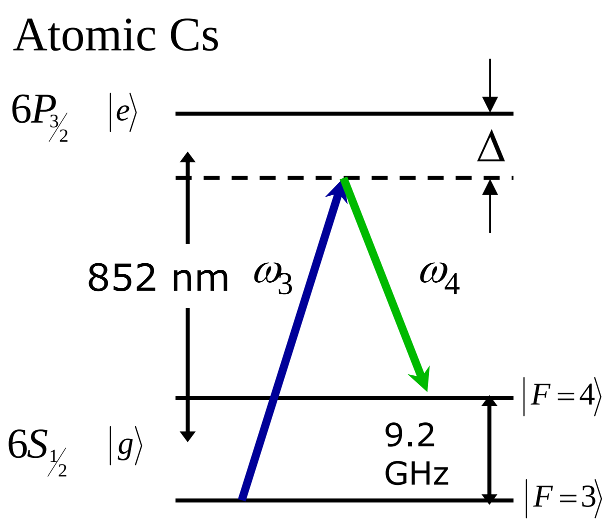


- Use radiation pressure to spatially separate F=3 from F=4 atoms.
- Simultaneously detect both ensembles with a common probe beam.

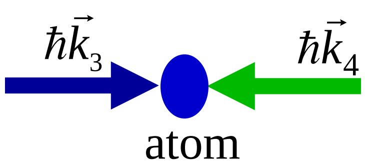
Biedermann, submitted to Opt. Lett.

Stimulated Raman transitions

Level scheme



Excitation Geometry



Doppler sensitive configuration

- $\mathbf{k}_3$, $\mathbf{k}_4$ counter-propagate

Ground states

- Avoid spontaneous emission
- Excitation between magnetic field insensitive sublevels

Large detuning D

- Effective 2-level system
  - F=3, m_f=0 ↔ F=4, m_f=0
- Effective traveling wave excitation
  - $\mathbf{k}_{eff} = \mathbf{k}_3 - \mathbf{k}_4 \sim 2\mathbf{k}_3$
- Effective transition frequency
  - $\Delta\omega_{eff} = \omega_3 - \omega_4$

Overview of atom interferometry

For a useful overview of the field, see the following review article:

A. Cronin, J. Schmiedmayer, D. Pritchard, “Optics and interferometry with atoms and molecules,” Rev. Mod. Phys. **81**, 1051–1129 (2009). arXiv:0712.3703

Young’s double slit with atoms

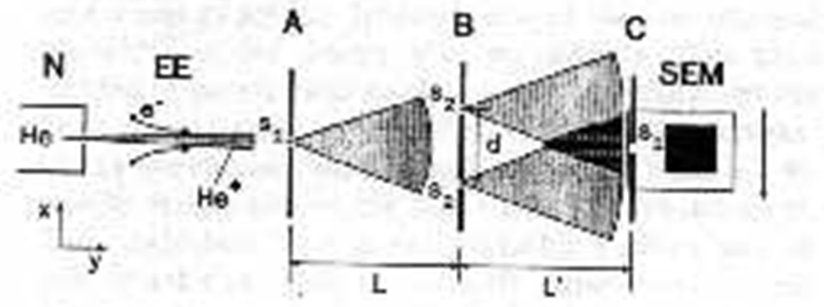


FIG. 2. Schematic representation of the experimental setup:

Young’s 2 slit with Helium atoms

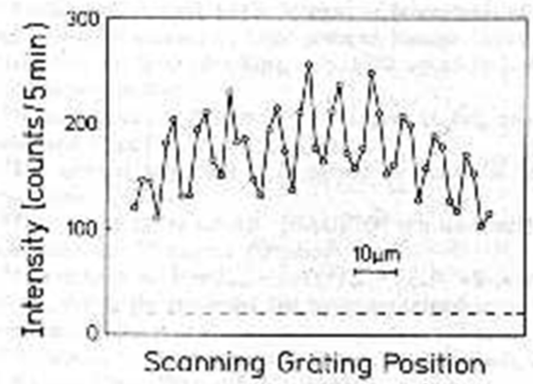
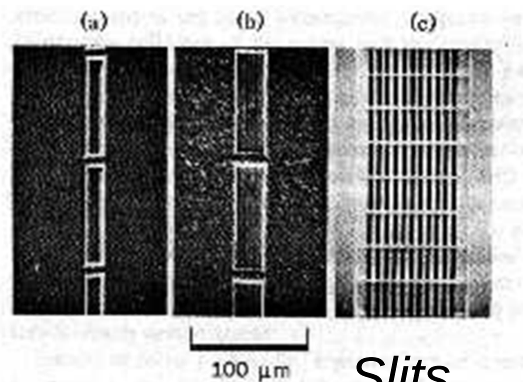


FIG. 5. Atomic density profile, monitored with the 8-μm grating in the detector plane, as a function of the lateral grating displacement. The dashed line is the detector background. The line connecting the experimental points is a guide to the eye.

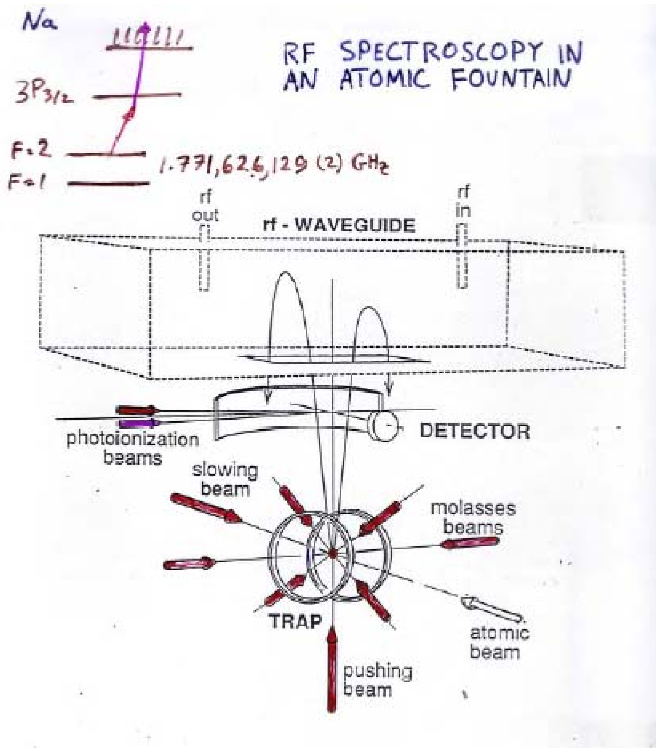
Interference fringes 2691

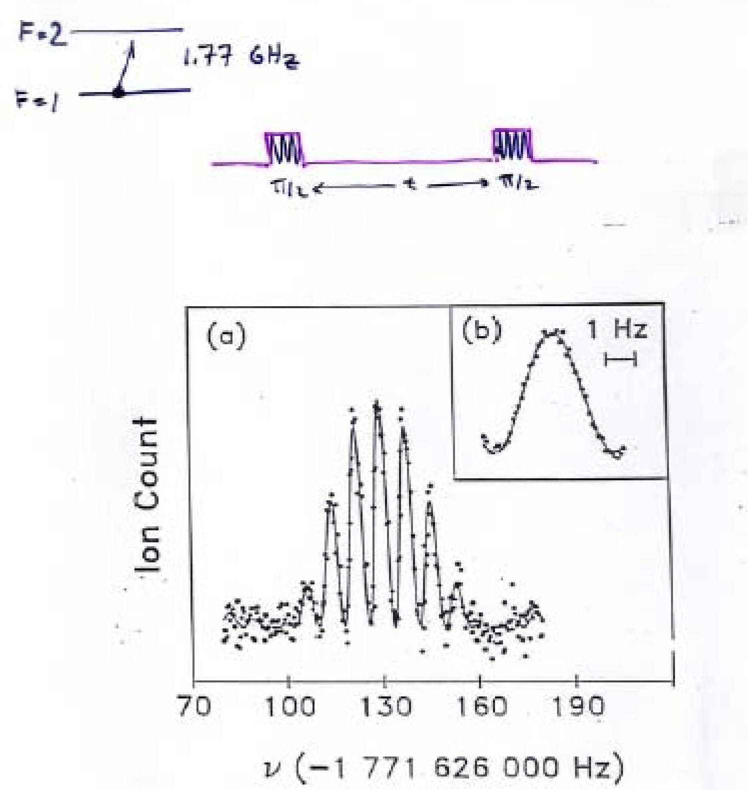


Slits

One of the first experiments to demonstrate de Broglie wave interference with atoms, 1991 (Mlynek, PRL, 1991)

1989 – Atomic fountain RF spectroscopy

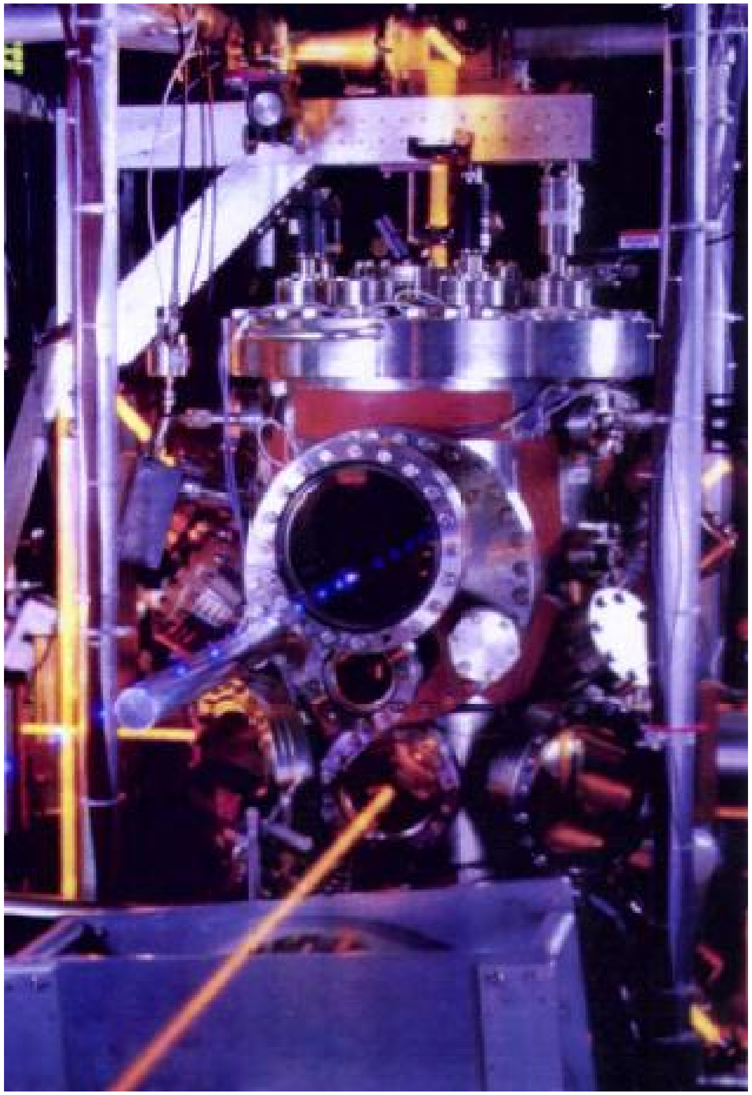


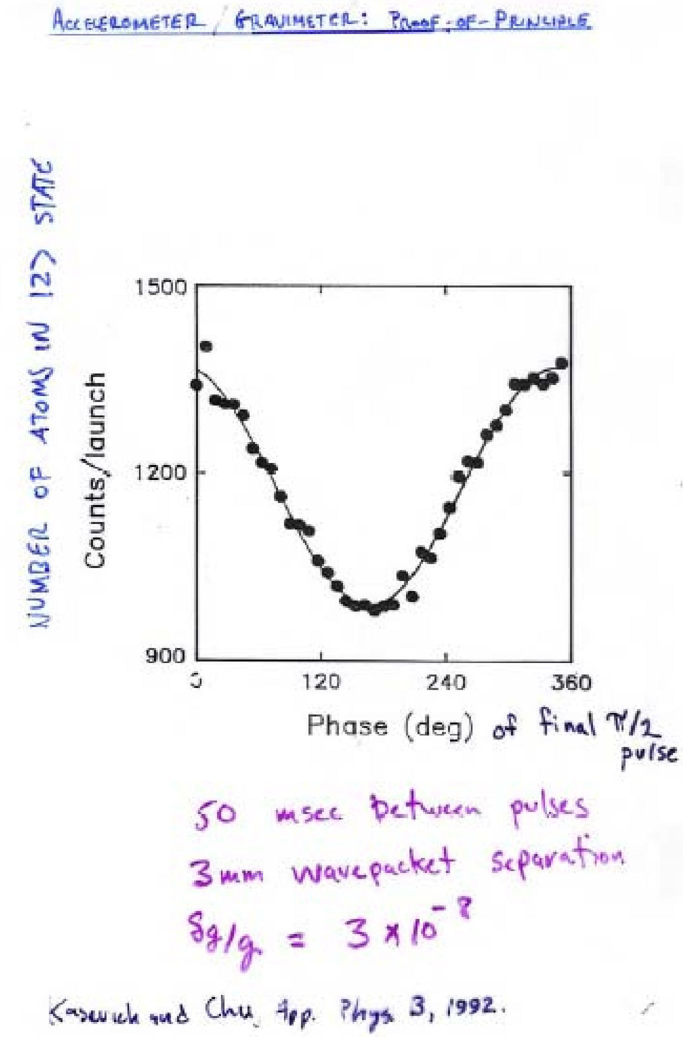


Precursor to NIST F1 Primary Frequency Standard

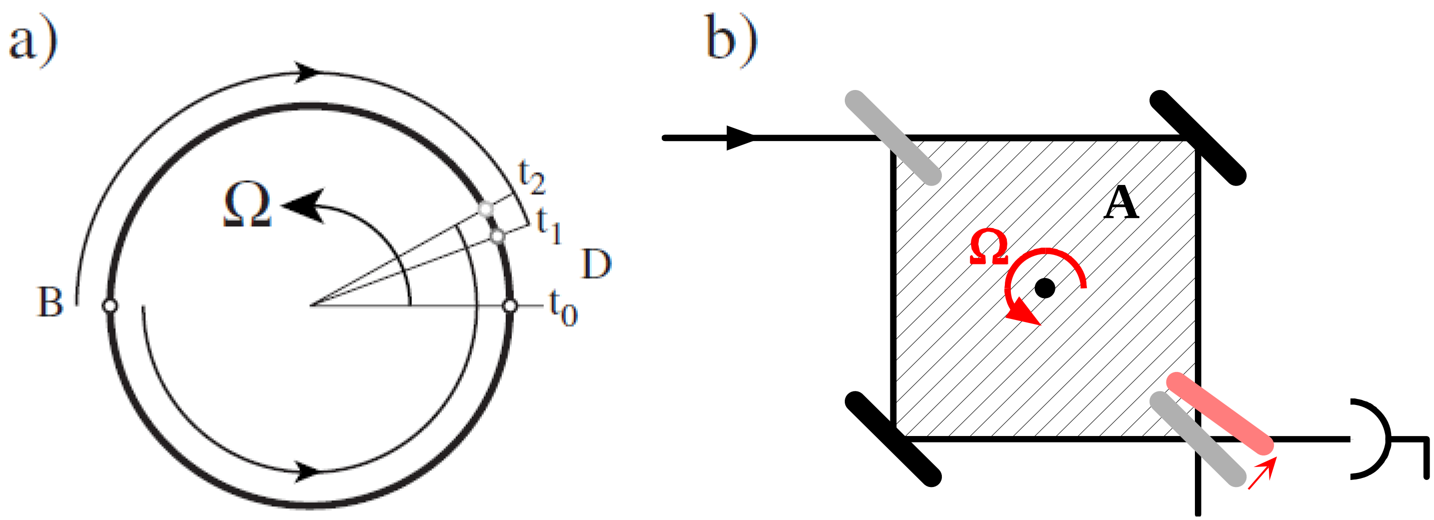
Kasevich, Riis, DeVoe, Chu, PRL 63, 612, 1989

1991 Light-pulse atom interferometer





Sagnac effect - light



FOG **Mach Zehnder**

B=Beamsplitter
D=Detector

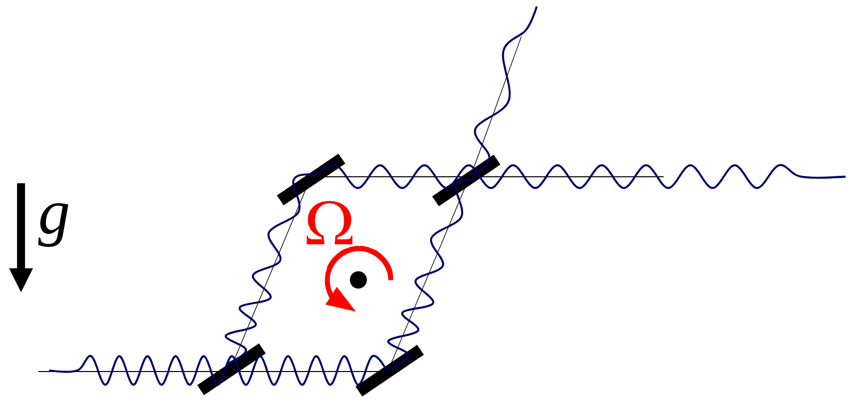
Sagnac effect - de Broglie wave sensors

Accelerometer/gyroscope

de Broglie wavelength: $\lambda = h/mv$

accel: λ increases with height

gyro: Sagnac effect



Current ground based experiments with atomic Cs:

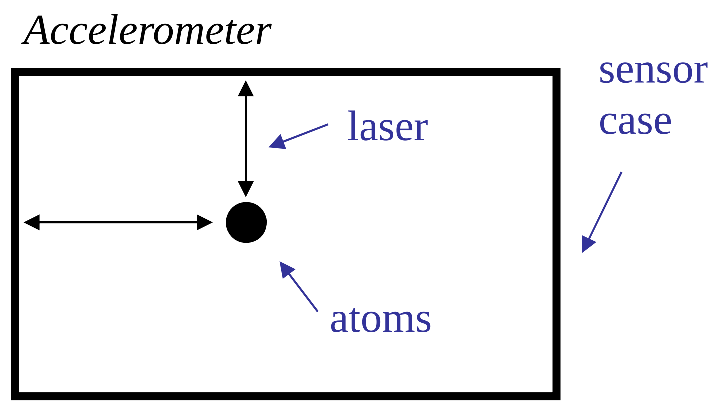
Wavepacket spatial separation ~ 1 cm

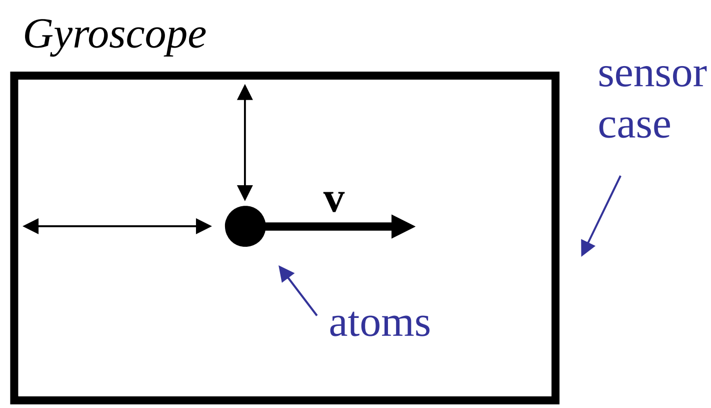
Phase shift resolution ~ 10^{-5} rad

(Previous experiments with neutrons)

Why superb sensors?

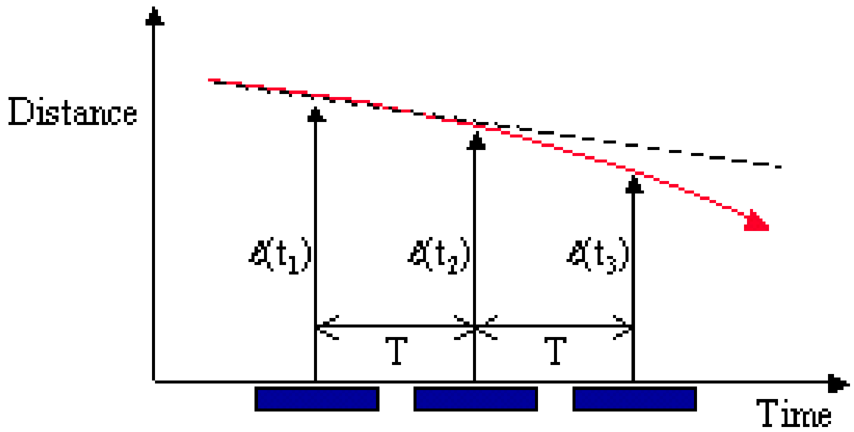
- **Atom in vacuum = near perfect inertial reference.**
- **Laser/atom interactions register relative motion between atom and sensor case.**
- **Sensor accuracy derives from the exceptional stability of optical wavefronts.**
- **Direct read-out of angular and linear displacements.**



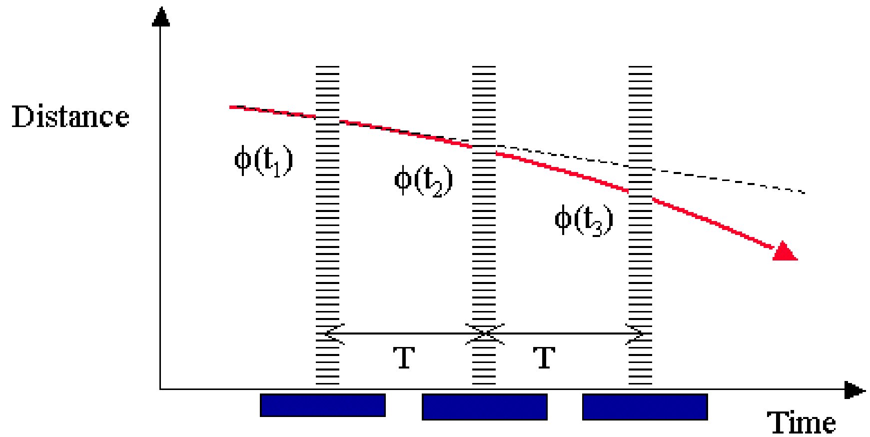


Approximate kinematic model

Falling rock



Falling atom



- Measure three distances:
  $\ell(t_1)$, $\ell(t_2)$ and $\ell(t_3)$
- Acceleration:
  $a \sim [\ell(t_1) - 2\ell(t_2) + \ell(t_3)]$

- Laser phases at atoms:
  $\phi(t_1)$, $\phi(t_2)$ and $\phi(t_3)$
- Atomic physics $\Rightarrow$
  $a \sim [\phi(t_1) - 2\phi(t_2) + \phi(t_3)]$

Ref: Kasevich and Chu, *Appl Phys B* **54** (1992).

Kinematic model phase shifts

Expression for phase shift following 3-pulse sequence:

$$\Delta\phi = \phi_1 - 2\phi_2 + \phi_3.$$

Subscript i indexes pulse number (eg. 1 corresponds to first pulse at t=0, 2 to second pulse at t=T and 3 to third pulse at t=2T. The ith component is given by (all vectors in inertial frame):

$$\phi_i = \vec{k}_i \cdot \vec{x}_i$$

where $\vec{k}_i$ is the propogation vector for the laser field (attached to body) and

$$\vec{x}_i = \vec{x}(t) - \vec{x}_i^0.$$

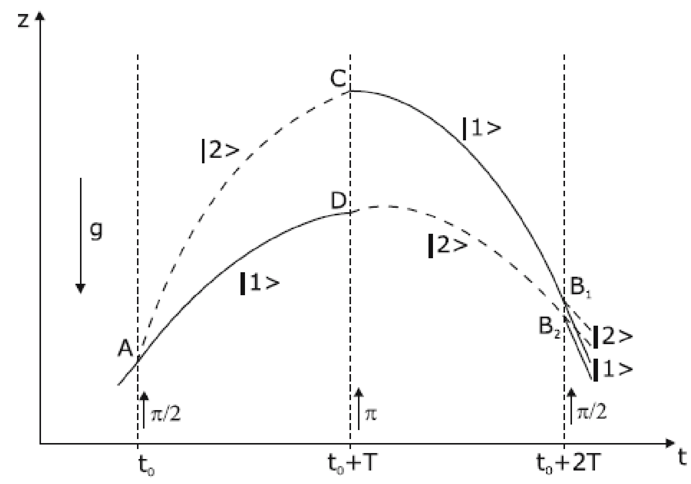
In this expression $\vec{x}(t)$ describes the inertial trajectory of an atom falling under the influence of gravity, with an initial velocity defined with respect to body axes at t=0, while the coordinates $\vec{x}_i^0$ indicates the position of the rigid body CG (to be concrete, the position of an optical fiber facet) To be explicit

$$\vec{x}(t) = \vec{x}_0 + \vec{v}t + \frac{1}{2}\vec{g}t^2.$$

Phase shifts: Semi-classical approximation

Three contributions to interferometer phase shift:

$$\Delta\phi_{\text{total}} = \Delta\phi_{\text{prop}} + \Delta\phi_{\text{laser}} + \Delta\phi_{\text{sep}}$$



Propagation shift:

$$\frac{S_{\text{cl,B}} - S_{\text{cl,A}}}{\hbar}$$

Laser fields (Raman interaction):

$$k(z_c - z_b + z_d - z_a) + \phi_I - 2\phi_{II} + \phi_{III}$$

Wavepacket separation at detection:

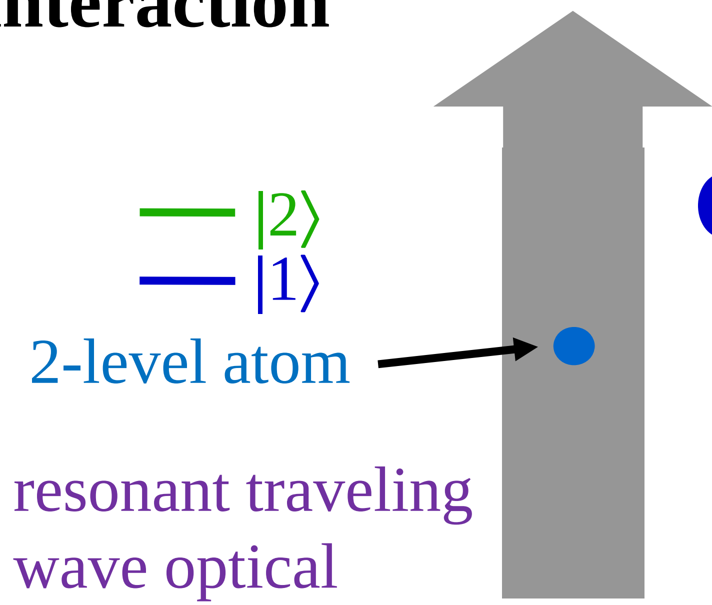
$$\vec{p} \cdot \Delta\vec{r}/\hbar$$

Bongs, et al., App. Phys. B, 2006.

Storey, Cohen-Tannoudji, J. Phys. II France, 1994.

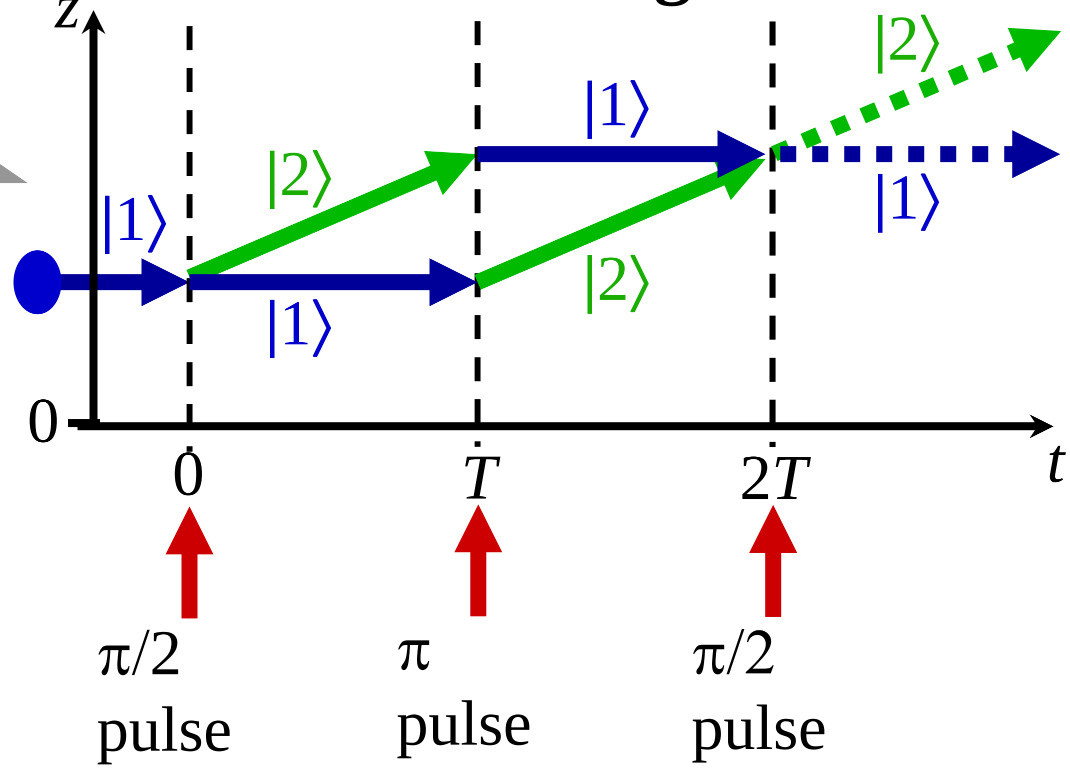
Light-pulse atom (LPA) interferometry

Resonant optical interaction



resonant traveling wave optical excitation, (wavelength λ)

Recoil diagram



Photon momentum recoil spatially separates the atomic wavepackets.

Interferometer signals

Measure number of atoms in one or both states (fluorescence)
→ Probability of atom transition
→ Phase (2π ambiguity)
→ Inertial signal(s)
→ Sum and difference opposite atom velocities to distinguish rotation, linear acceleration

$$P_e = \frac{1}{2}\left[1 - \cos\left(\underbrace{\frac{2m}{\hbar}\boldsymbol{\Omega}\cdot\boldsymbol{A} + \phi_1 - 2\phi_2 + \phi_3}\right)\right]$$

$$\Delta\Phi = -\boldsymbol{k}_{\text{eff}}\cdot\boldsymbol{a}T^2 + \phi_1 - 2\phi_2 + \phi_3$$

$$\boldsymbol{a}_{\text{Cor}} = -2\boldsymbol{\Omega}\times\boldsymbol{v}$$

$$\text{ARW} = \sqrt{3600}\,\frac{180}{\pi}\,\frac{1}{\text{SNR}\cdot 2\text{vkT}^2}\sqrt{T/2}$$

[Degrees/sqrt(h)]

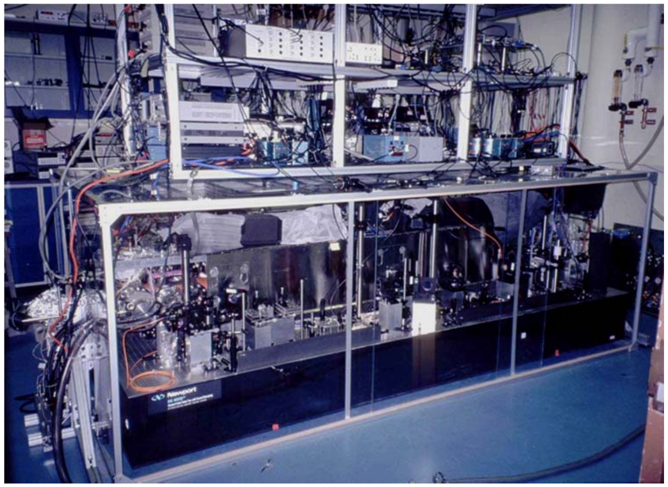
SNR ~ 1/sqrt(N) "Quantum projection noise"

AI Gyro approaches

- Atom source
  - Thermal beam
    - Velocity selection, transverse cooling
  - Launch
    - BEC [complex; mean-field shift]
    - MOT
      - Vapor cell loading
      - 2D-MOT loading
- Guiding
  - Atom chip / waveguide
  - Free space
- Atom optics
  - Nanofabricated transmission gratings
  - Light pulses
    - Bragg transitions [requires very cold, well-collimated]
    - Raman transitions
  - Pulse sequence
    - 3 pulse
    - Large momentum transfer (LMT)

Atomic beam gyro

Laboratory gyroscope

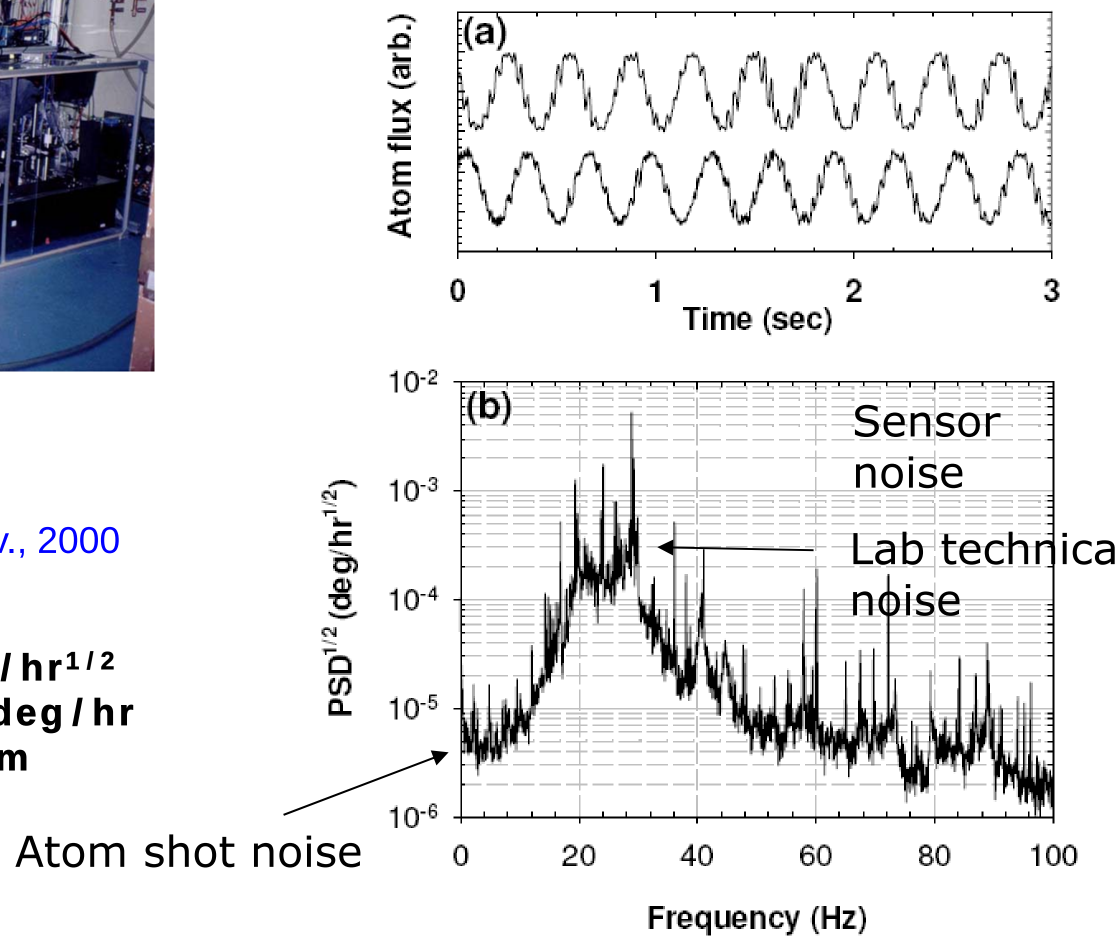


AI gyroscope

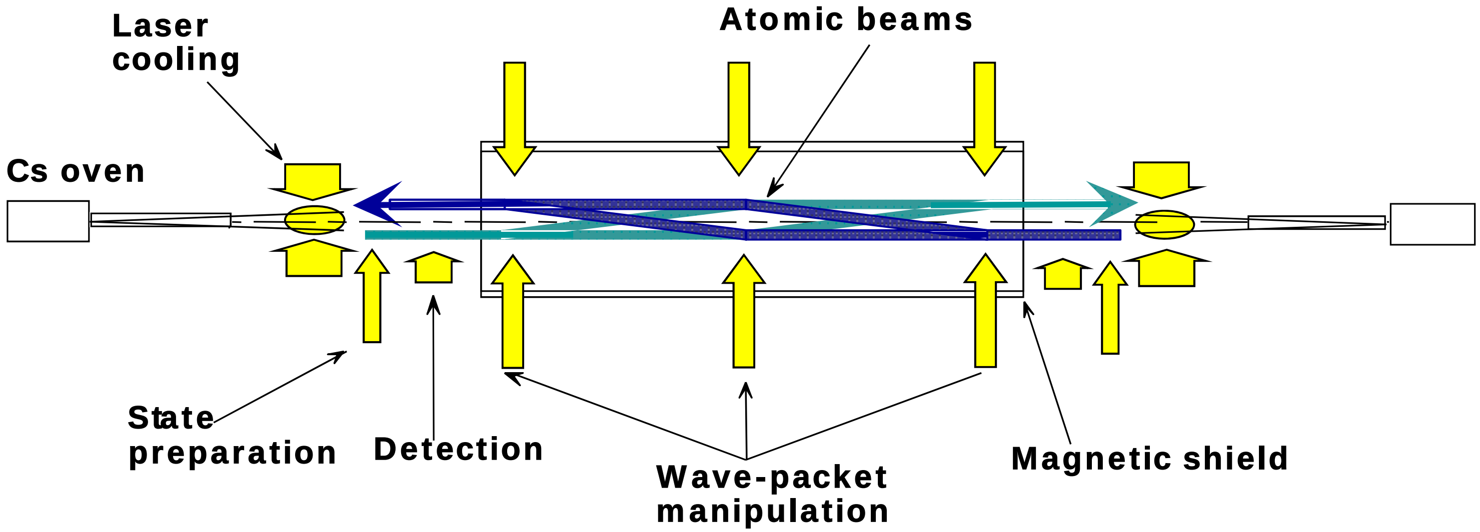
Gustavson *et al*, PRL, 1997
Gustavson *et al*, Class QM Grav., 2000
Durfee *et al*, PRL, 2006

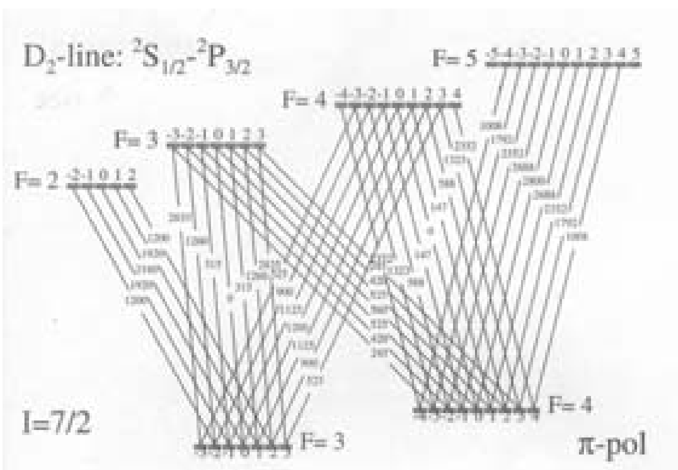
ARW **3 μdeg/hr$^{1/2}$**
Bias stability: **< 60 μdeg/hr**
Scale factor: **< 5 ppm**

Gyroscope interference fringes:



Some apparatus details

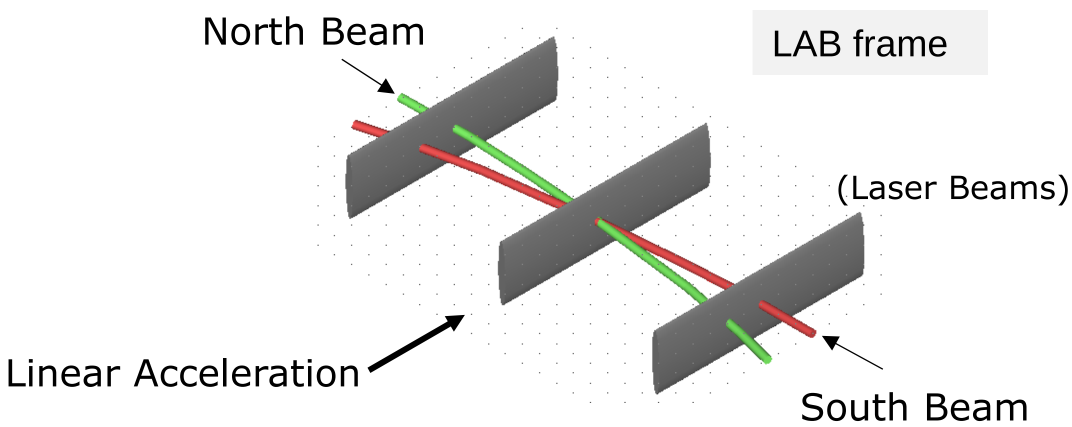




- State preparation
  - Transverse laser cooling (0.3 mrad collimation)
  - Optically pump to F=3
- 2 m interaction region
  - B shield, bias
  - 10^{-9} torr chamber isolated from table
- Raman beams
  - spatial filtered
  - alignment ~10^{-4} rad
- Detection
  - probe fluorescence imaged onto photodiode
- Lasers
  - Diodes at 852 nm (100-150 mW)

Separation of Accelerations and Rotations

Acceleration



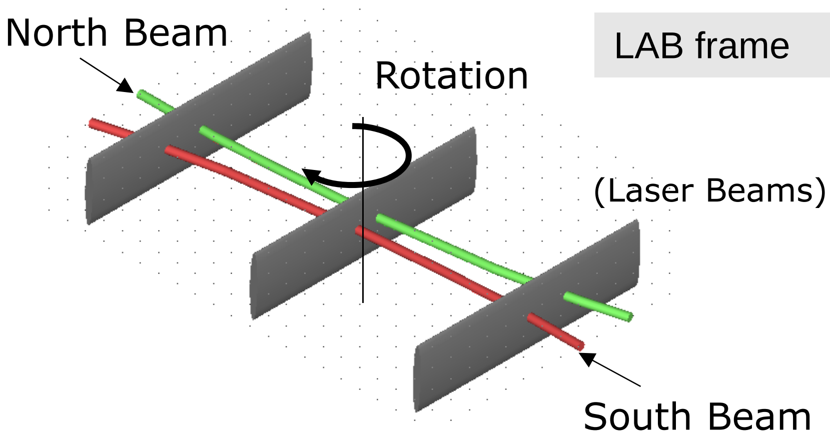
Q: How to discriminate between linear accelerations and rotations?

A: Compare signals from counter-propagating atomic beams.

Rotation: Difference of North and South signals

Acceleration: Sum of North and South signals

Rotation



Atom beams deflect due to Coriolis force. Deflection direction reversed with beam velocity

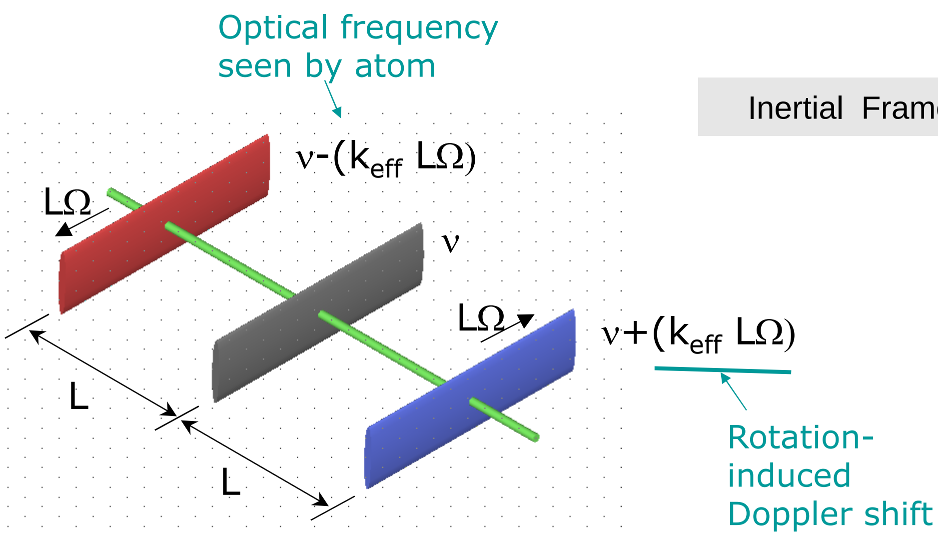
Electro-optic Rotation Bias

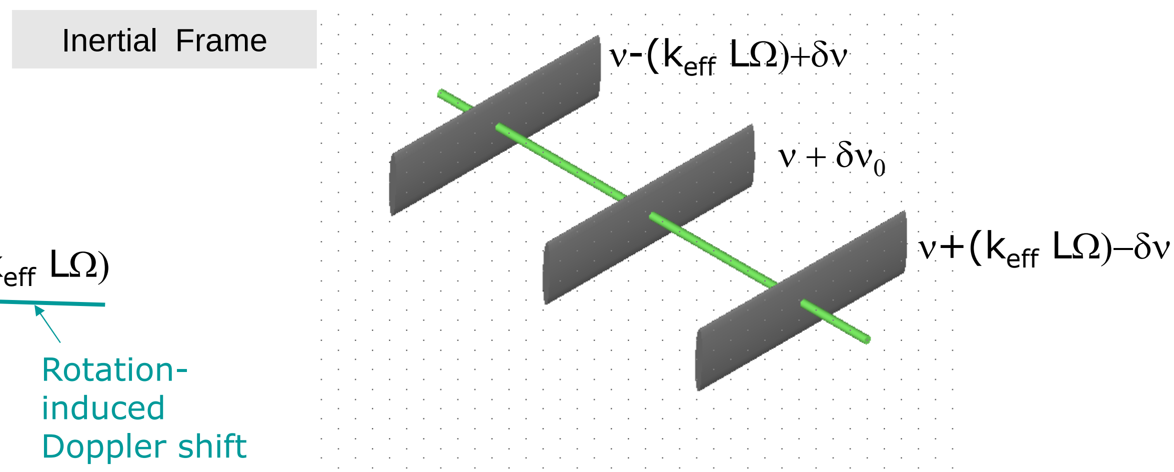
Inertial reference frame

- Optical (Raman) frequencies Doppler shifted

Compensate Doppler shifts

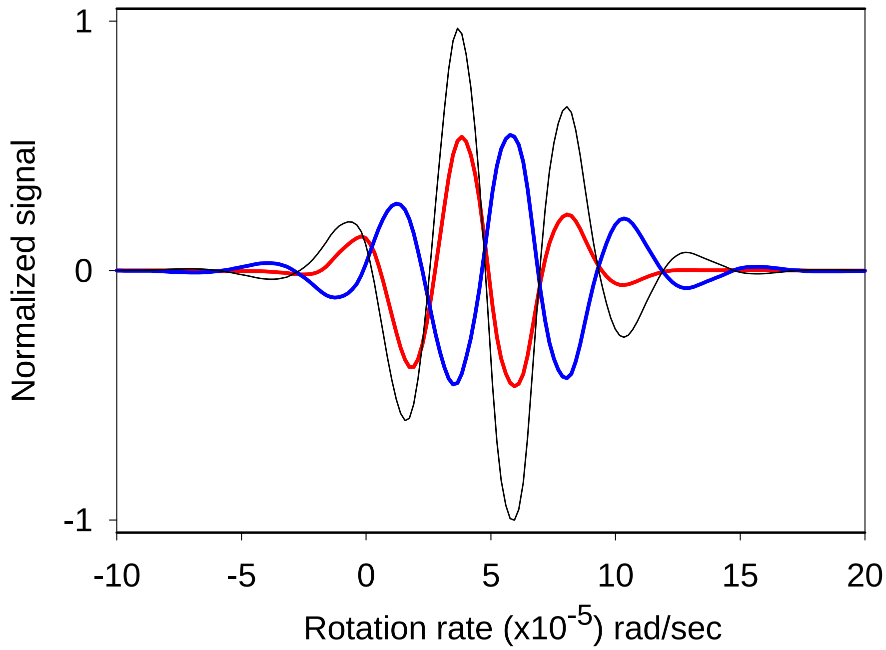
- Electro-optically shift frequencies to compensate Doppler





Choose $\delta\nu = (k_{eff}\, L\Omega)$ to balance apparent frequencies
Rotation readout via $\delta\nu$
Additional offset frequency $\delta\nu_0$ to scan fringes

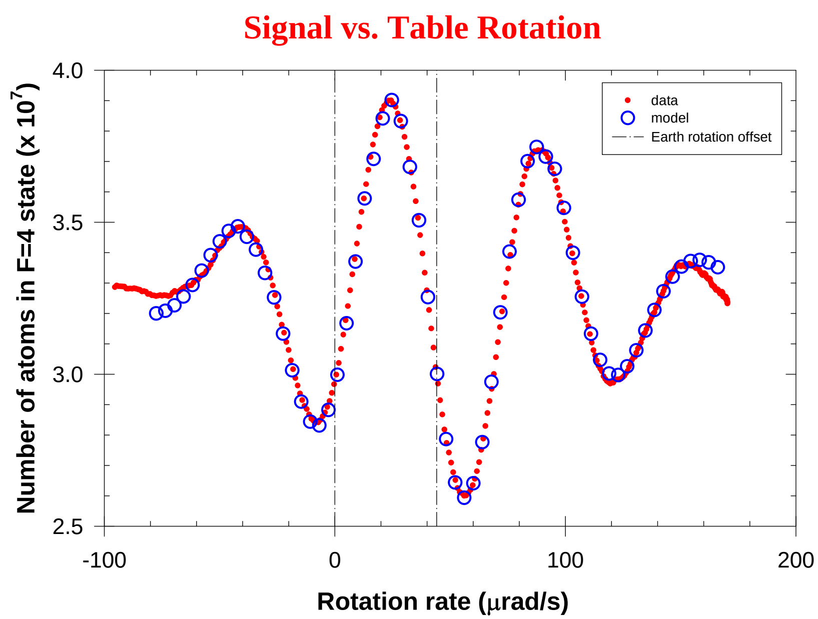
Interference Constrast Envelope



Interference contrast envelope for dual beam, electro-optically scanned fringes. (Gustavson, et al. Class. Quantum Grav. **17**, 2000)

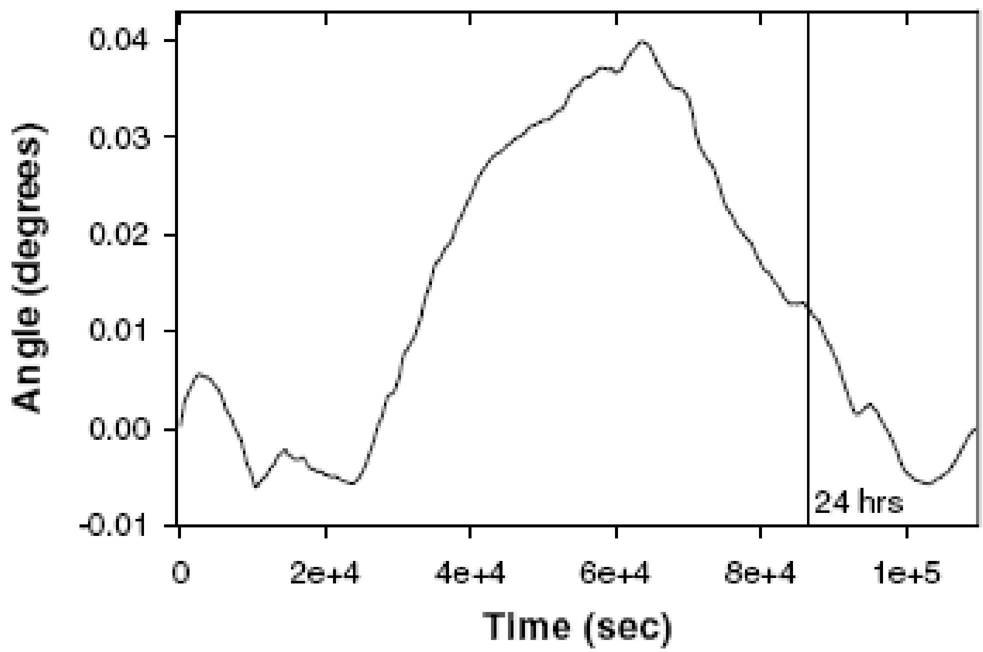
Gustavson *et al.*, PRL **78**, 2046 (1997).

Earlier work: mechanically scanned single fringe.



Long-term drift

Noise performance was excellent…
What about long term drifts?



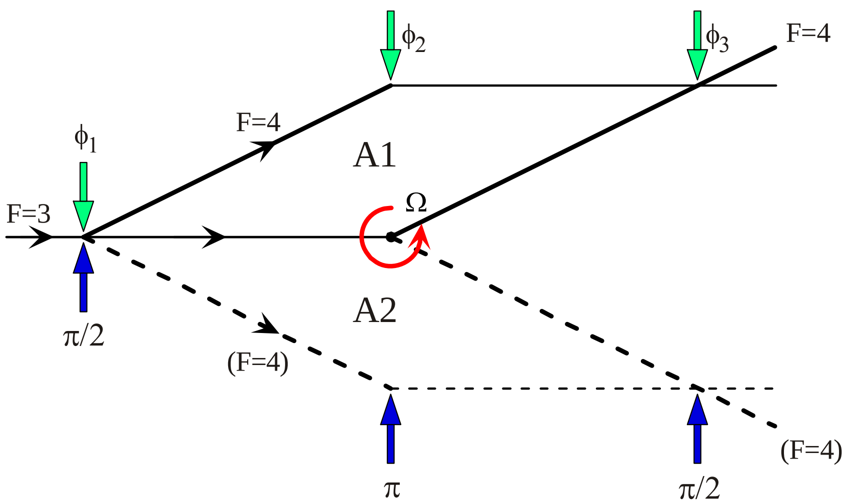
A 24 hour data run shows large (30 mdeg) angle errors.

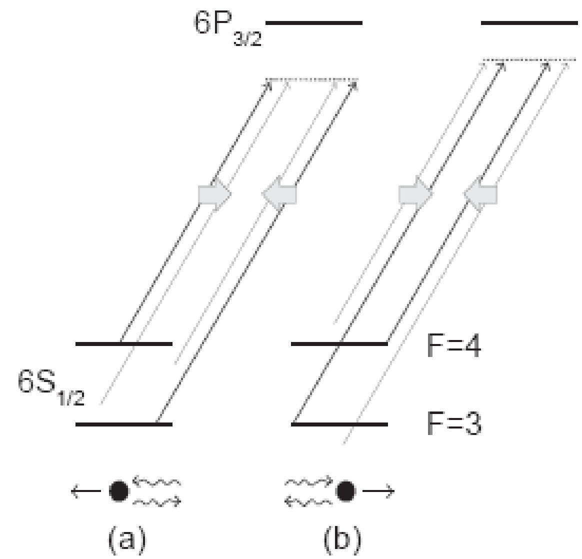
What is driving drifts?

How can drifts be suppressed?

Case (area) Reversal

Case reversed geometry uses electro-optic techniques to accurately reverse the effective propagation vector. This suppresses non-inertial phase shifts.



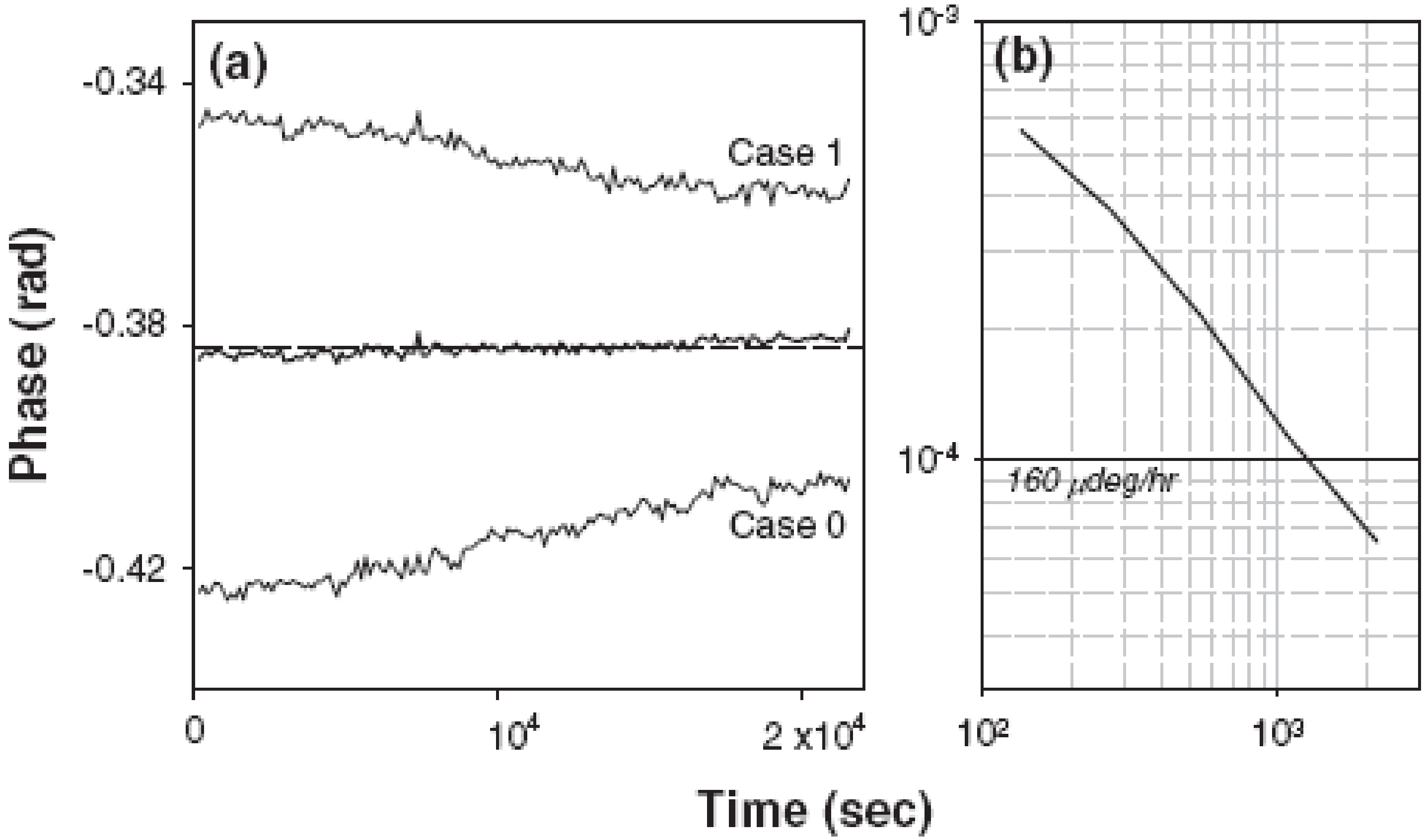


Bias offset drift:

- All precision deployed Sagnac gyroscopes use case reversal methods to suppress bias offset drifts
- Case reversal repeatability usually determines gyro accuracy

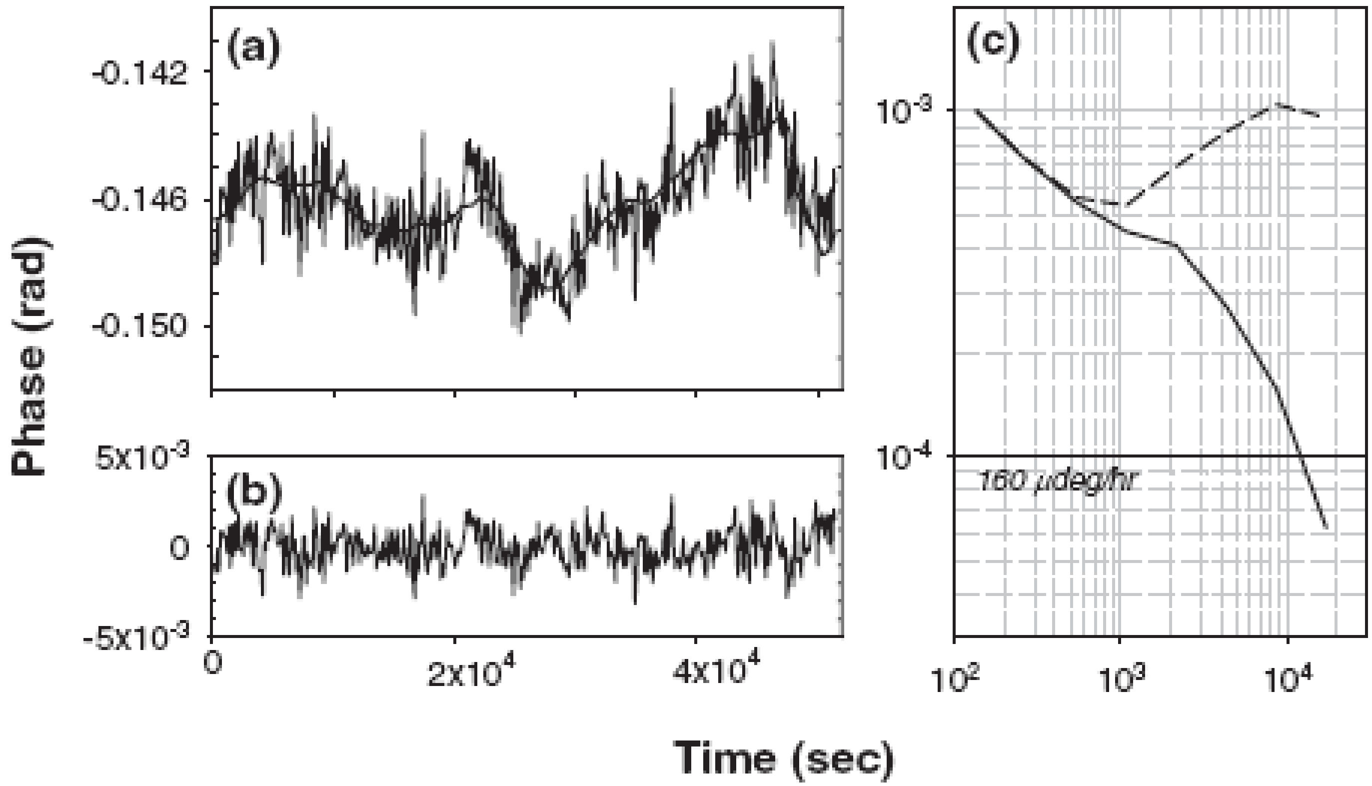
Frequency shifts in Raman beam frequencies accomplish reversal of effective propagation vector.

Case-reversed Gyroscope performance



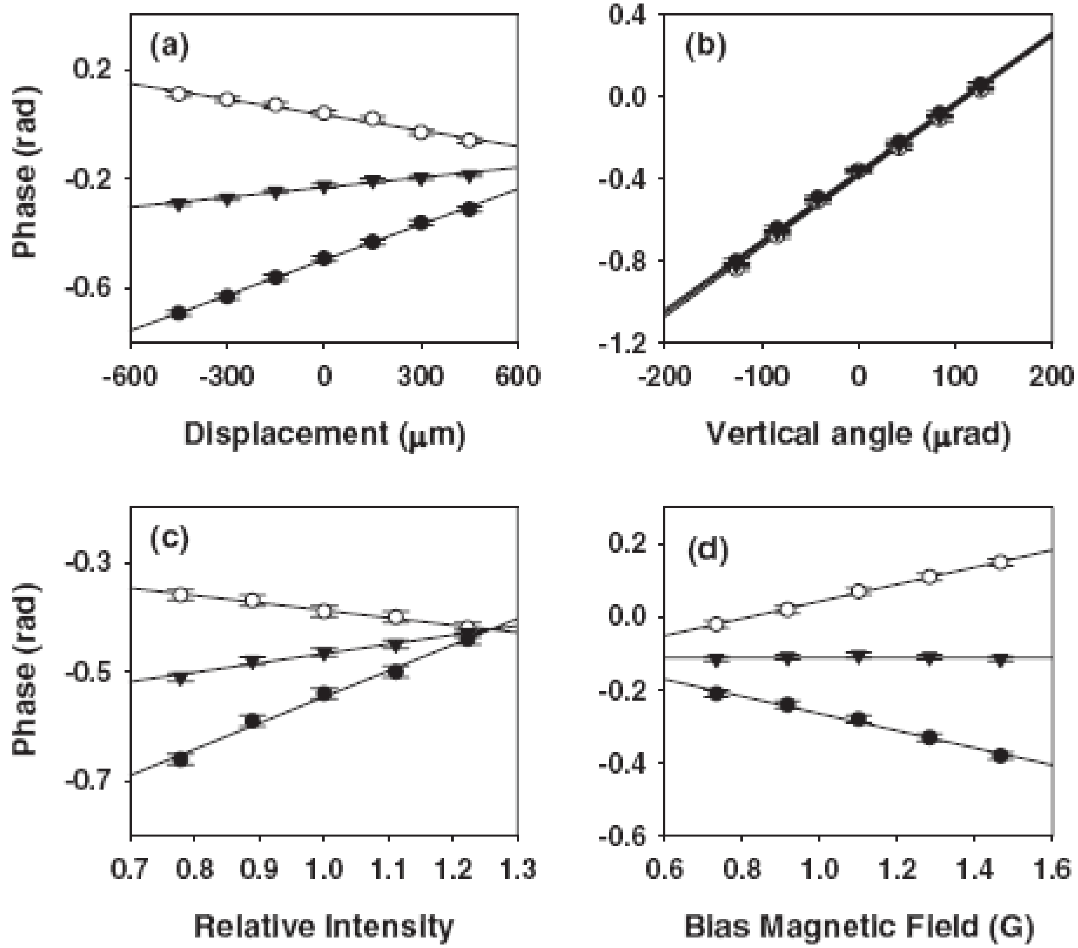
Case-reversal to cancel common-mode noise

Temperature compensation



Correlate gyroscope output with thermal fluctuations of apparatus (measured at 5 key locations)
Correct temperature induced errors using a simple least squares algorithm.

Gyroscope errors



Data establishes scaling coefficients for apparatus errors.

Misalignment and imbalances are driven by thermal fluctuations.

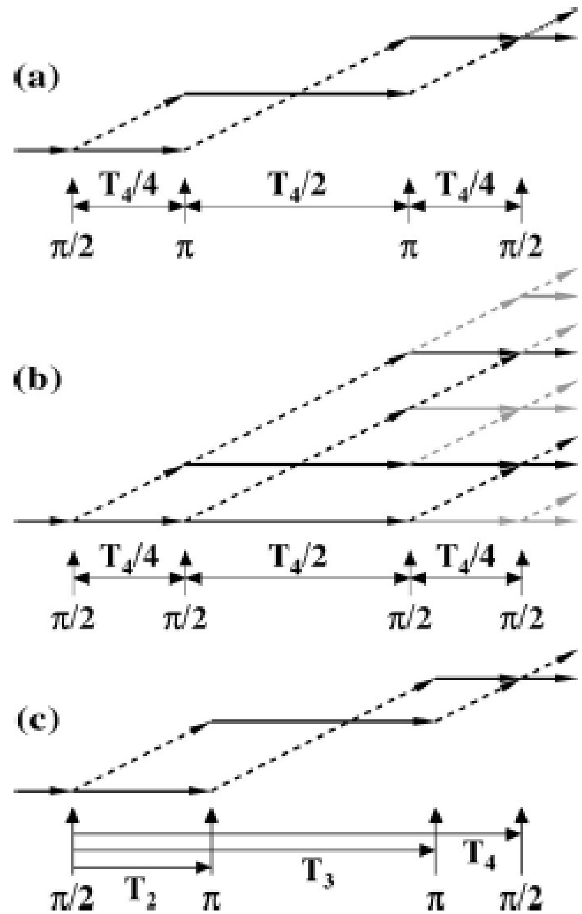
(a) Displacement of π pulse
(b) Angle of first $\pi/2$
(c) Relative intensity of Raman beams
(d) Magnetic field

Alignment errors can be explained with kinematic theory. Thermally driven errors likely responsible for observed long term performance.

Other configurations...

Time-domain pulsed sensors:
3-pulse
4-pulse
Analysis: Dubetsky, PRA 2006.

What are trade-offs for time domain vs. space-domain sensors?



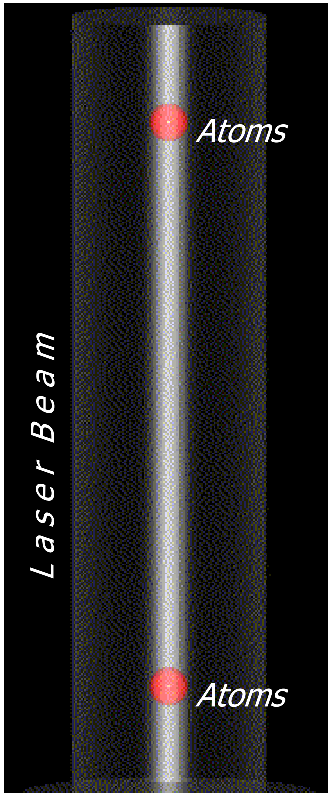
4-pulse gyroscope configurations.

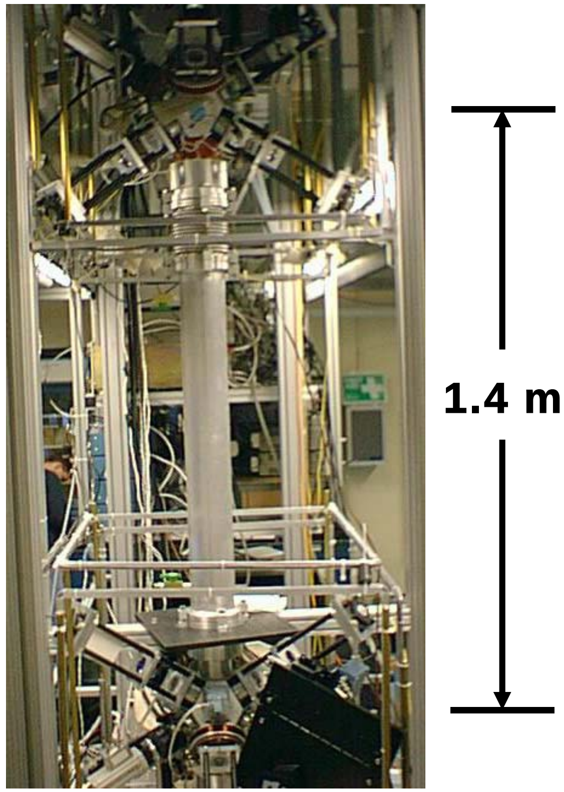
Hybrid Gradiometer / Gyro

J.K. Stockton, K. Takase, M.A. Kasevich, PRL **107** (2011)

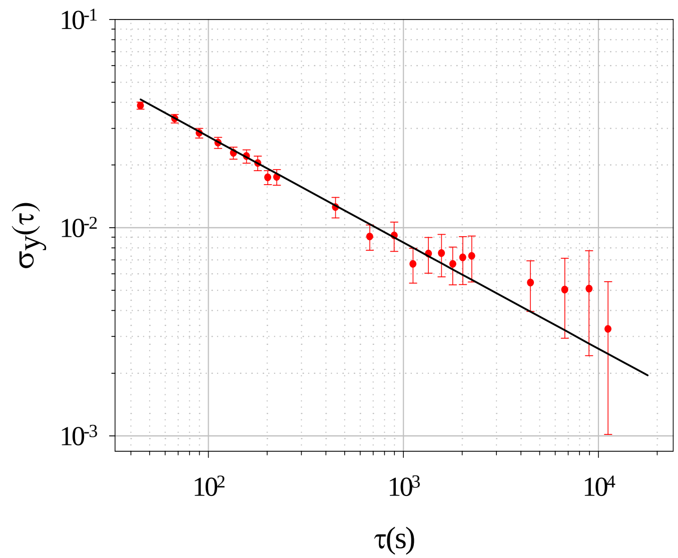
TLG: sensor design

1998 – Stanford/Yale laboratory gravity gradiometer





Distinguish gravity induced accelerations from those due to platform motion with differential acceleration measurements.



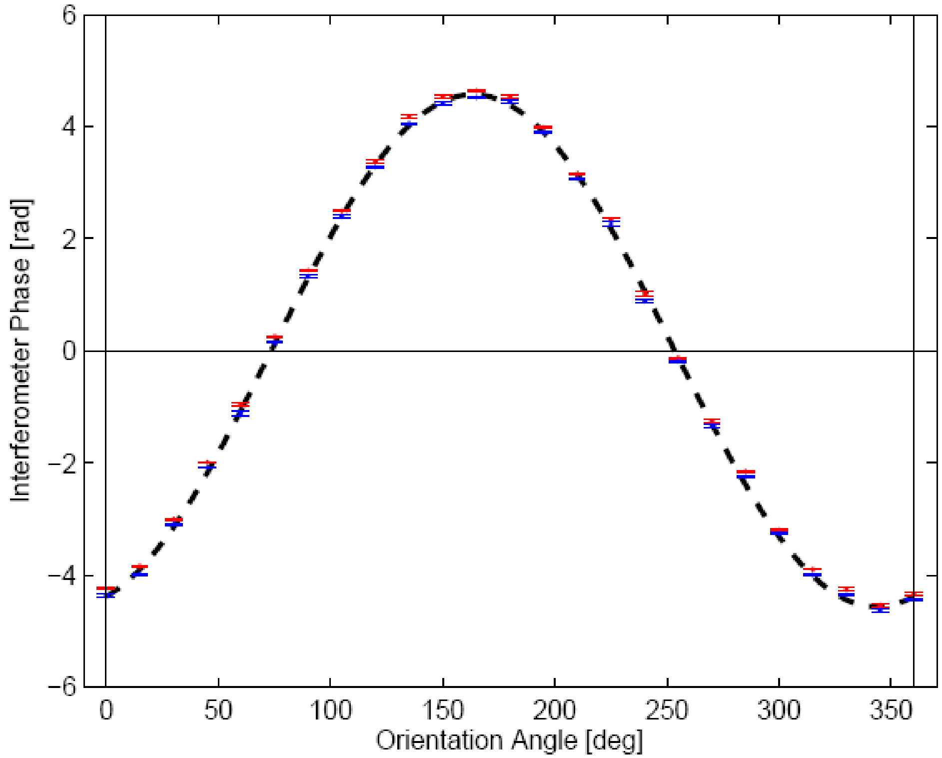
Demonstrated differential acceleration sensitivity:

4×10^{-9} g/Hz$^{1/2}$

(2.8×10^{-9} g/Hz$^{1/2}$ per accelerometer)

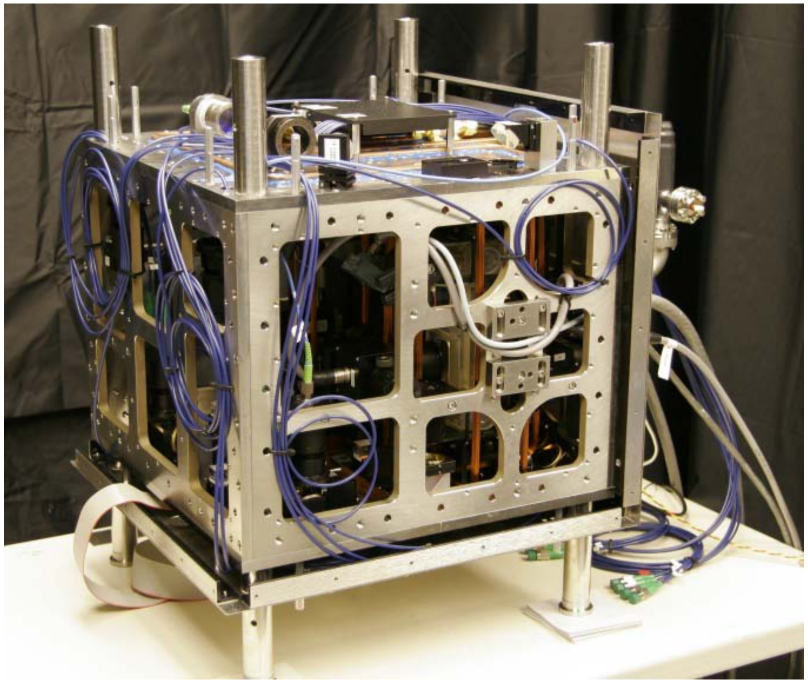
Hybrid sensor (2007)/Gyroscope mode

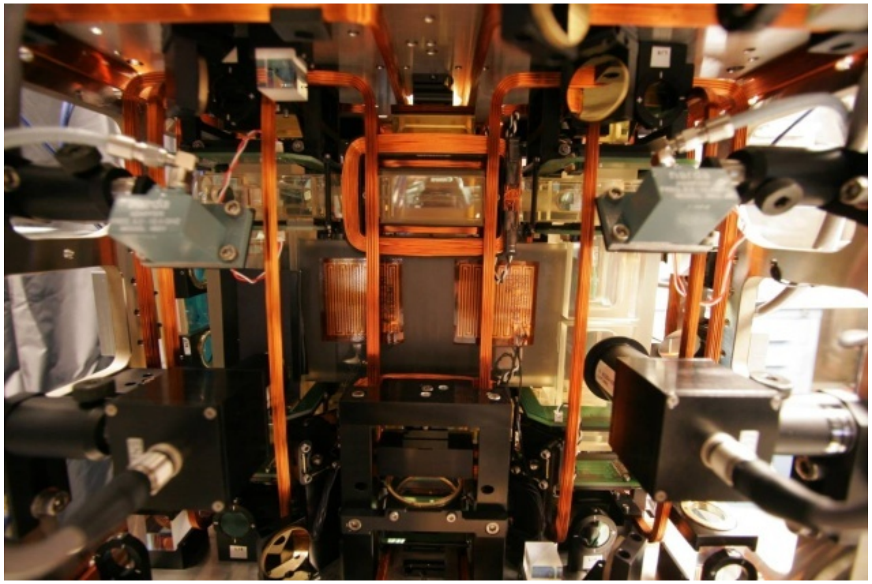
Measured gyroscope output vs.orientation:



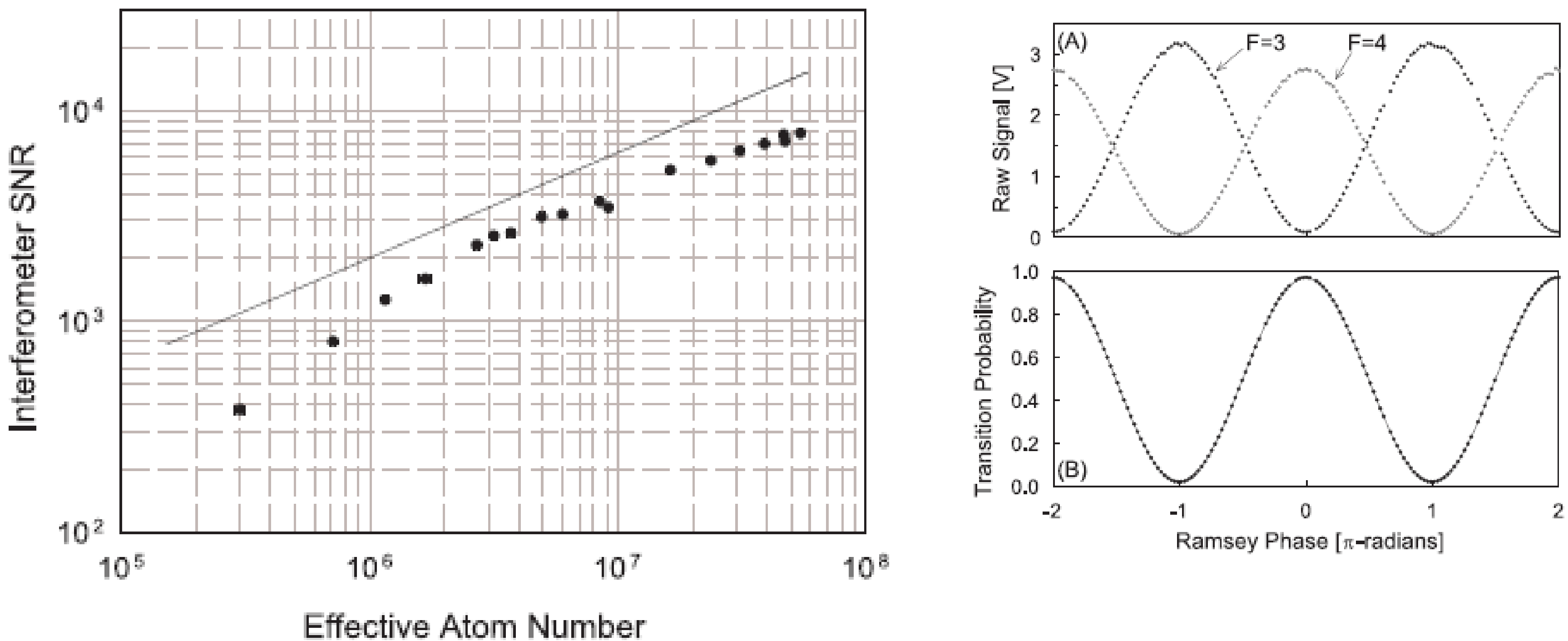
- Inferred ARW: < 100 μdeg/hr$^{1/2}$
- 10 deg/s max input
- <100 ppm absolute accuracy

Hybrid sensor details



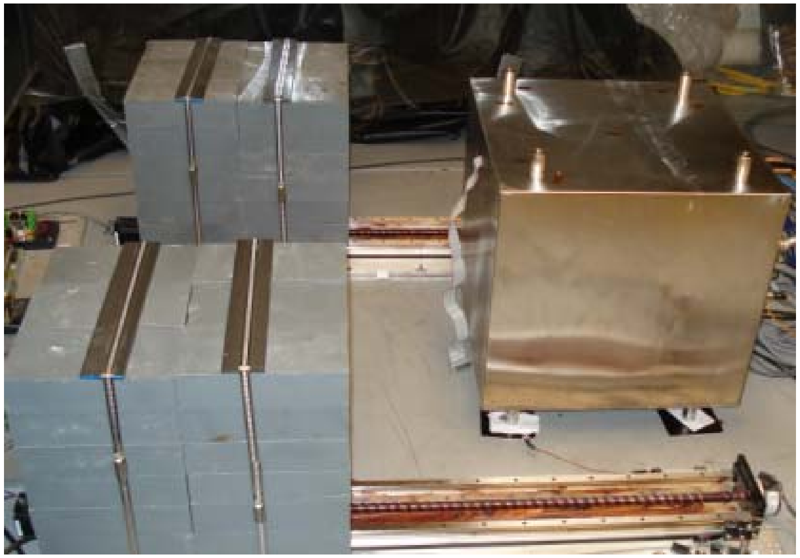


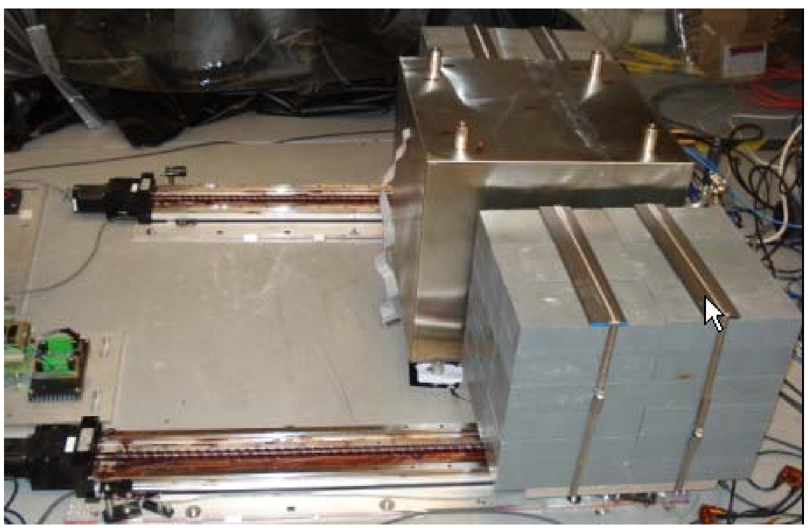
Normalized detection performance

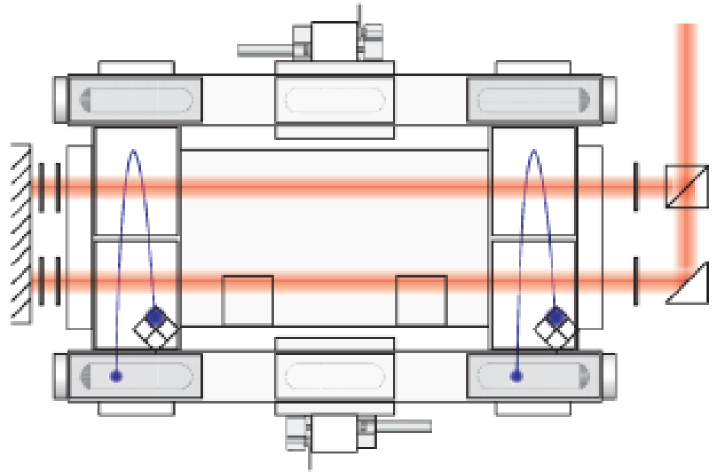


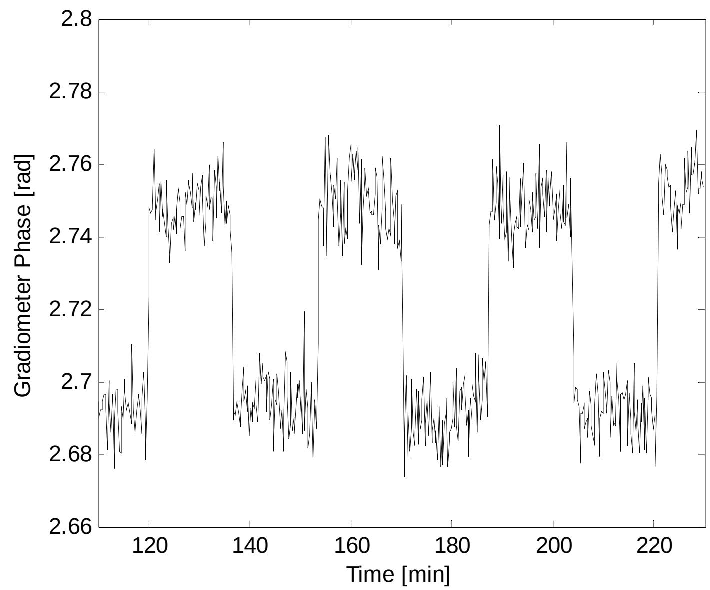
Can achieve near shot-noise limited performance.
SNR ~ 8,000:1 per shot demonstrated.

Hybrid sensor (2007)/Gravity gradient mode

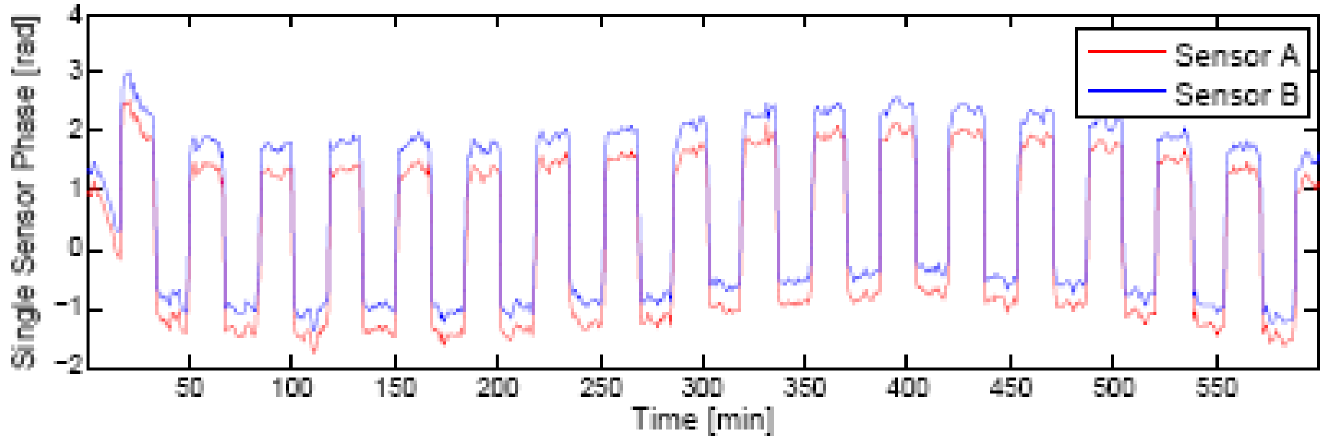








Hybrid sensor (2007)/Absolute accelerometer



Direct accelerometer outputs.

Horizontal input axis, microGal resolution.

Navigation with Light-Pulse AI

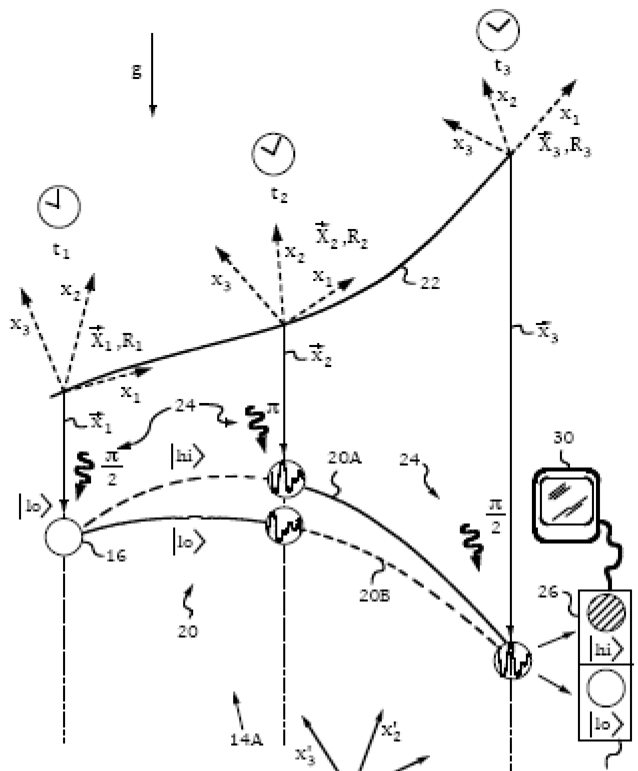


FIG. 2

- **Trajectory determined through interactions of free atom with laser light fields attached to the navigation platform**

- **Relative position between atom and platform determined through laser-atom interactions**

- **Like GPS, this navigation strategy is kinematic (no force rebalance).**

AOSense Hardware / Software

AOSense PNT Programs

- DARPA
  - High Dynamic Range Atomic Sensors (HiDRA)
    - "This contract is for the High Dynamic Range Atomic Sensors (HiDRA) effort will build on the Precision Inertial Navigation System (PINS) work by demonstrating that atom optic (AO) sensors can outperform existing technologies in the presence of realistic platforms dynamics for a broad range of military applications. The goal of this program is to provide jam-proof, non-emanating inertial navigation with near-GPS accuracies for future military systems." *Source: www.defense.gov*
  - Chip-Scale Combinatorial Atomic Navigator (C-SCAN)
    - Program goals (*Source: www.fbo.gov BAA)*
      - Rotation sensitivity: 10^{-4} deg/hour
      - Acceleration 10^{-6} g
      - long-term bias and scale-factor stability: 1 ppm
      - Start-up time <10 s from a cold start
  - Quantum-Assisted Sensing and Readout (QuASAR)
    - Optical standard
- Air Force
  - SBIR I/II: Compact Gyro/Accel for Inertial Navigation Based on Light Pulse AI
  - Compact High performance Atom Interferometer for Navigation (CHAIN)
- NAVY, NASA, ...

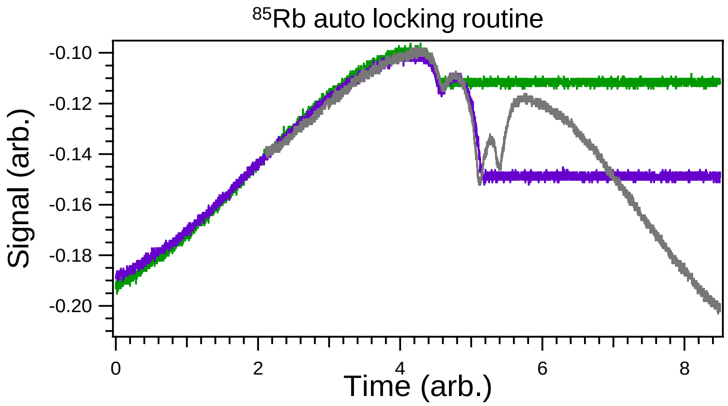
Electronics/Software: Laser Frequency Control

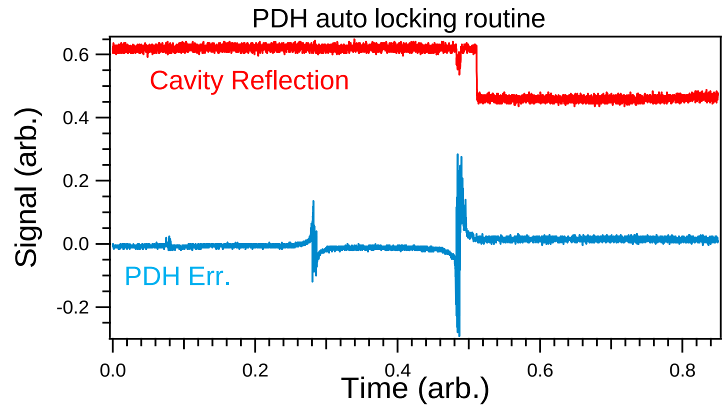
Laser lock system features:

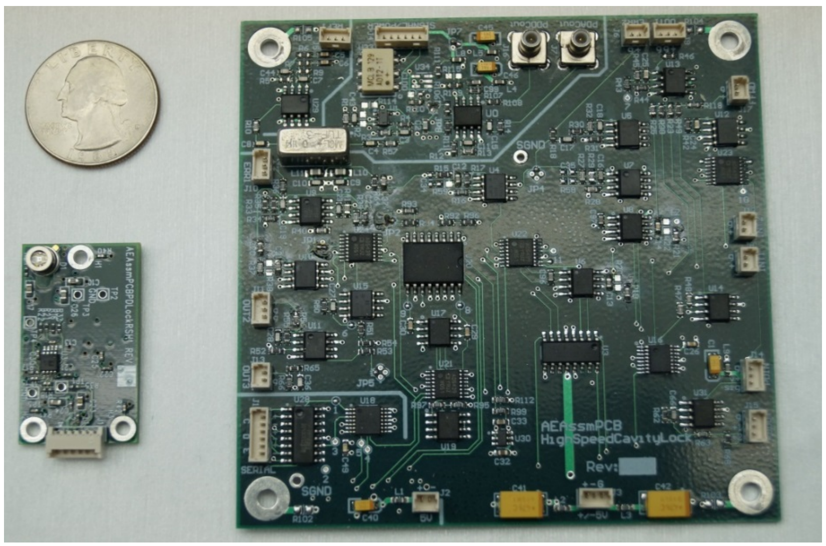
- Digital control of the loop transfer function, lock engage, modulation frequency, and reference phase
- On board secondary servo path for dual actuator systems
- Ramp and automatic locking routines
- ~2 MHz Servo BW – plan to increase

Lock Photodiodes:

- >50 MHz BW
- Shot noise limited @ 35µW
- Both AC and DC outputs



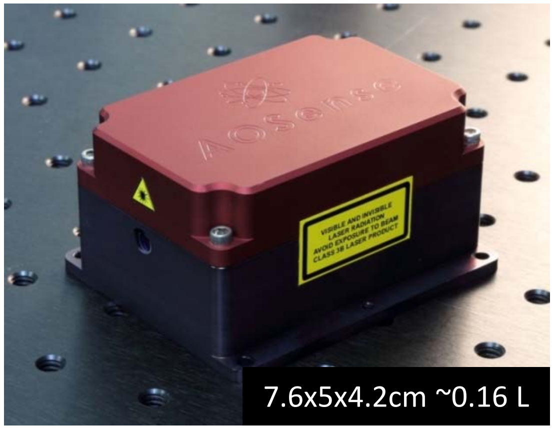


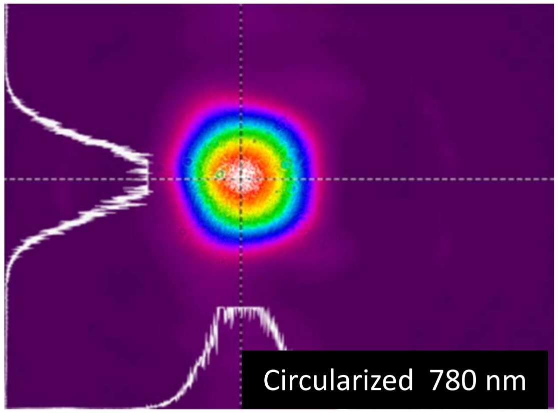


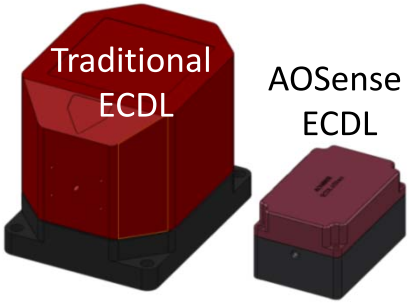
Lock PD

Lock board

AOSense External Cavity Diode Laser







200 kHz linewidth (50 ms)

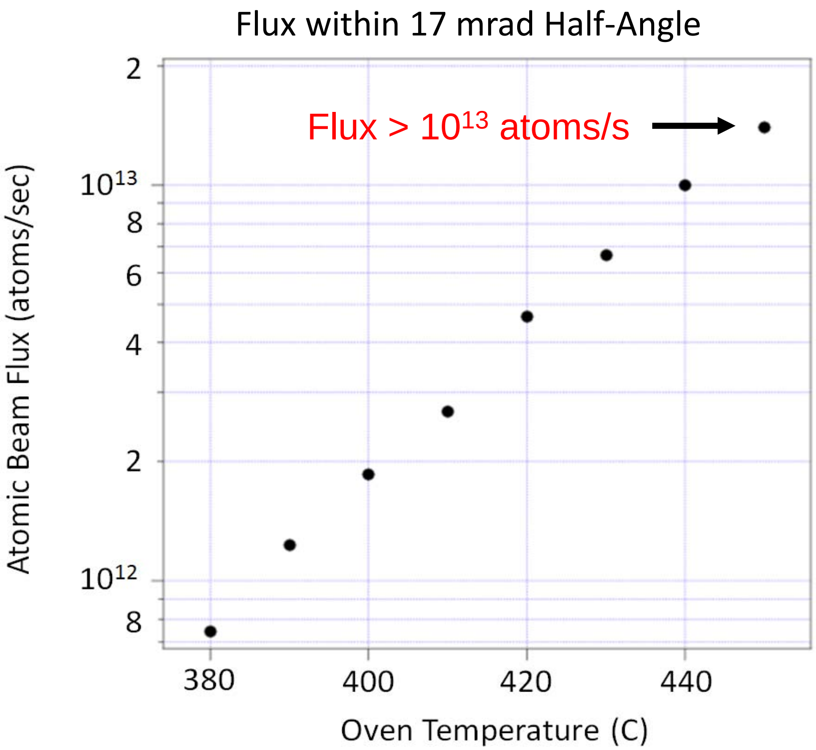
< 150 MHz/°C

17 GHz Mode-Hop Free Tuning

Circularized Output

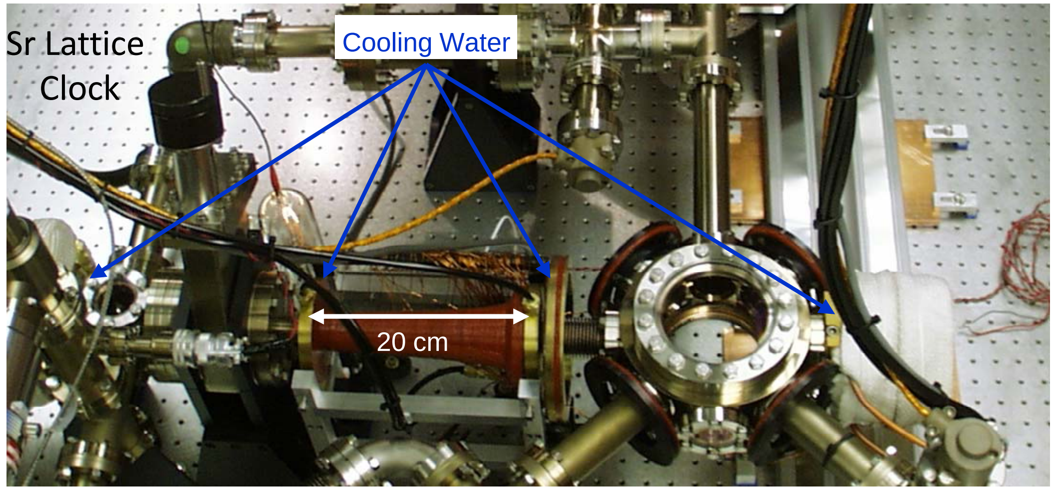
5x smaller than COTS ECDLs
Interference filter design

High flux / Low power oven



Compact Zeeman slower *

Traditional laboratory Zeeman slower:



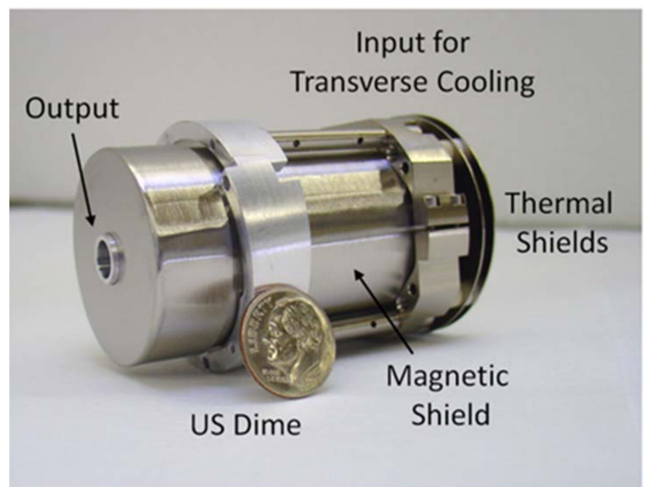
400-500 C Effusion Oven, Transverse Cooling
4 liters, 260 W

Zeeman slower
1.8 liters, 97 W

200 C Window
1 liter, 150 W

AOSense compact Zeeman slower*:

- Permanent magnet design
- No cooling water
- Small
- High flux



*** Patent pending. Tom Loftus, *et al*.**

Commercial gravimeter

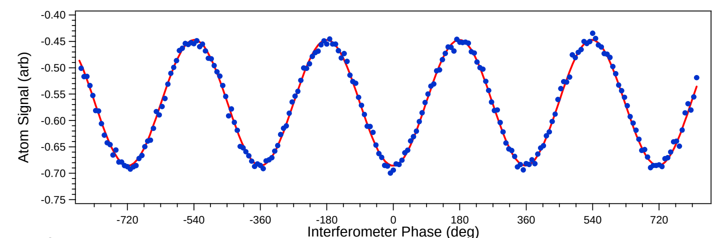
Laser system/ sensor head

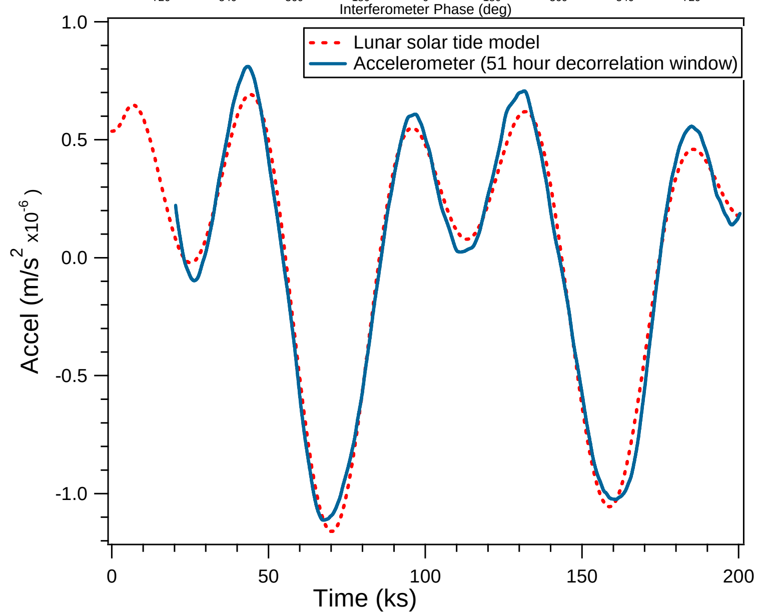
Control electronics

Magnetic shield (Φ4″×13″)

Cold atom absolute gravimeter

- Noise ≈ 1 μg/Hz$^{1/2}$
- Resolution < 0.1 μg
- Shipped 11/22/10





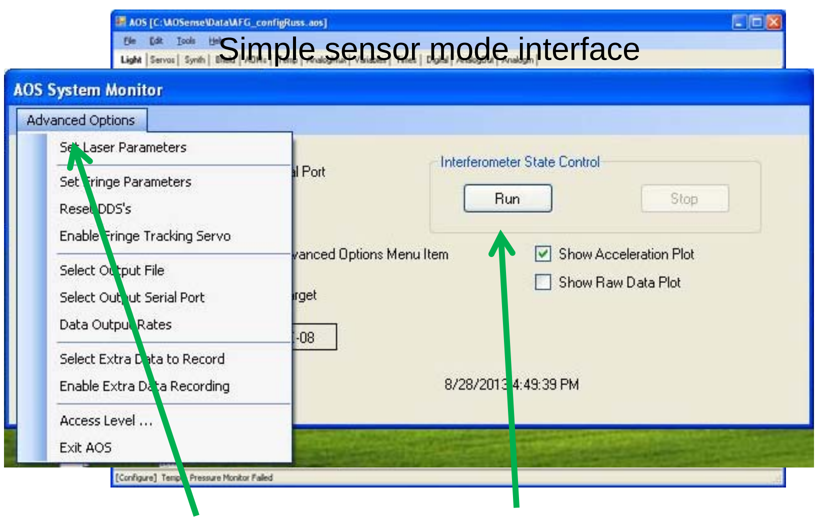
AOSense

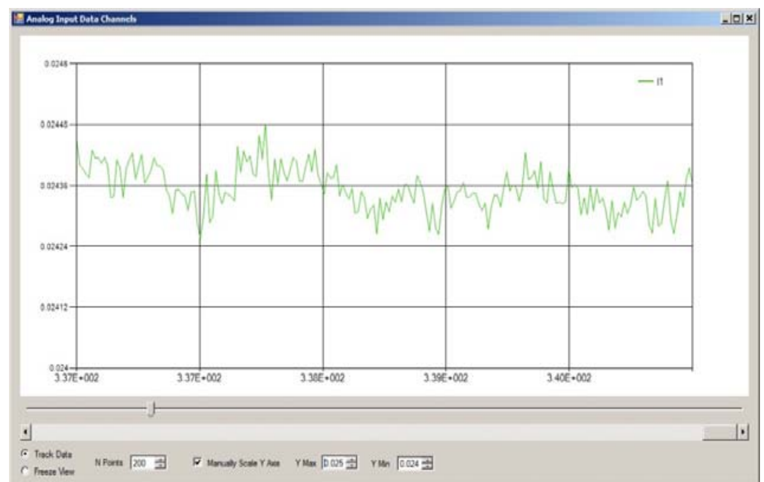
Integrated Computer and AOS Software

AOSense integrated computer control

- FPGA based system + AOS Software
- Provides all digitals, analogs I/O, serial
- Controls all lasers, temp, synthesizers, etc.
- Versatile parameters scans and plotting
- Designed for advanced cold atom systems
- Overpowered for SBOC, but flexible
- “Sensor mode” capability for non-experts and long term operation

User Interface

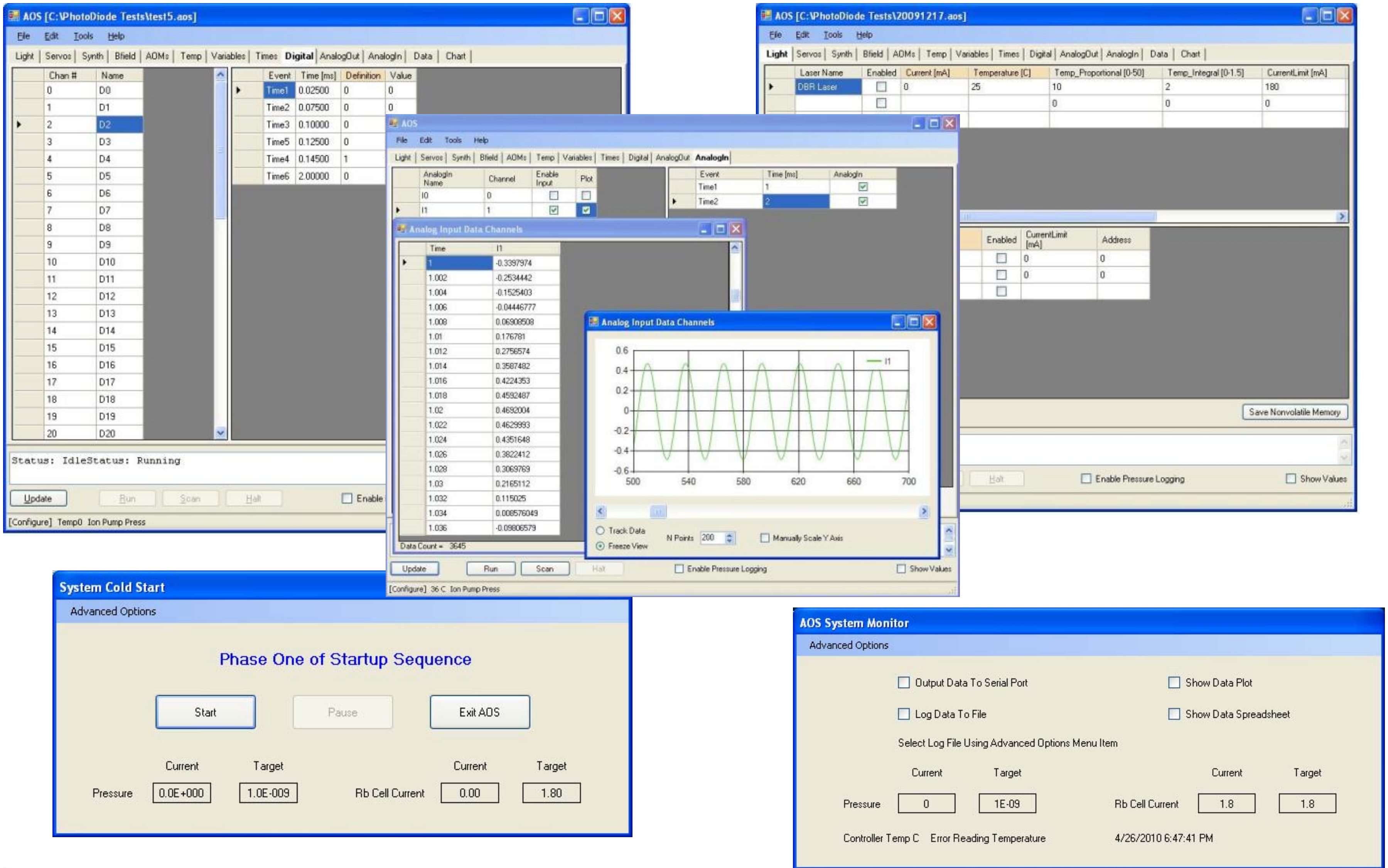




Data logging and calibrations tab

Run sensor button

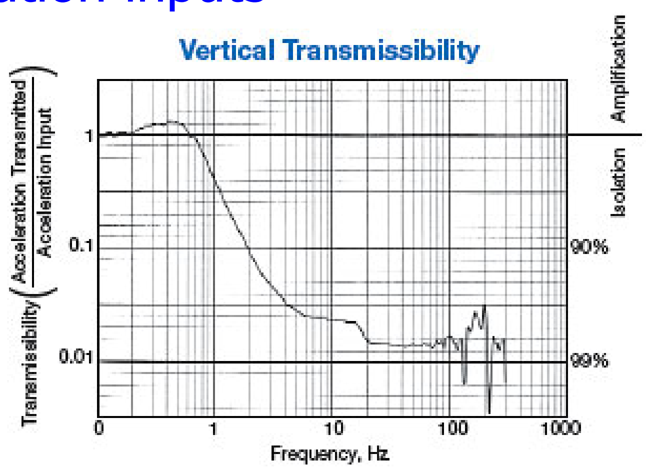
AOS – System control SW package

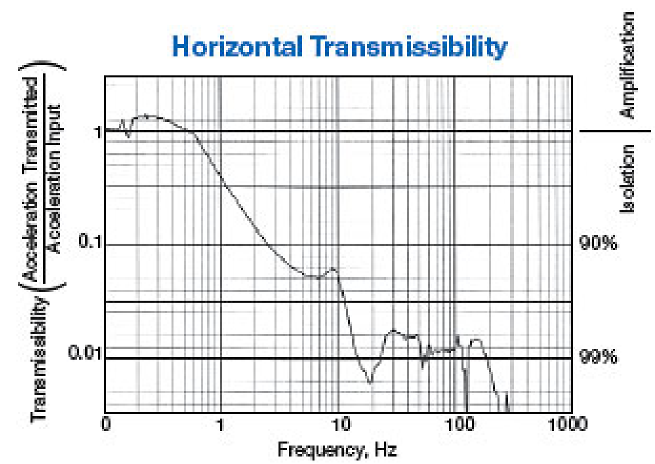


Sensor Test Equipment

Sensor testing: Low vibration limit and calibration

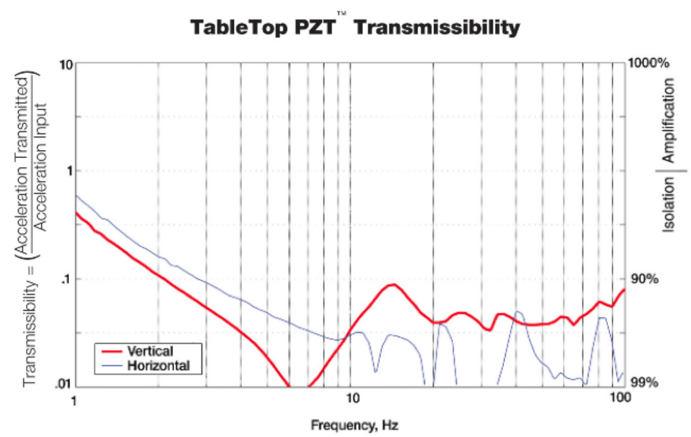
- TMC Stacis 2100
  - Vibration isolation to <1 Hz
  - Micron-level vibration inputs





TableTop PZT

Compact Hard-Mount Vibration Cancellation System



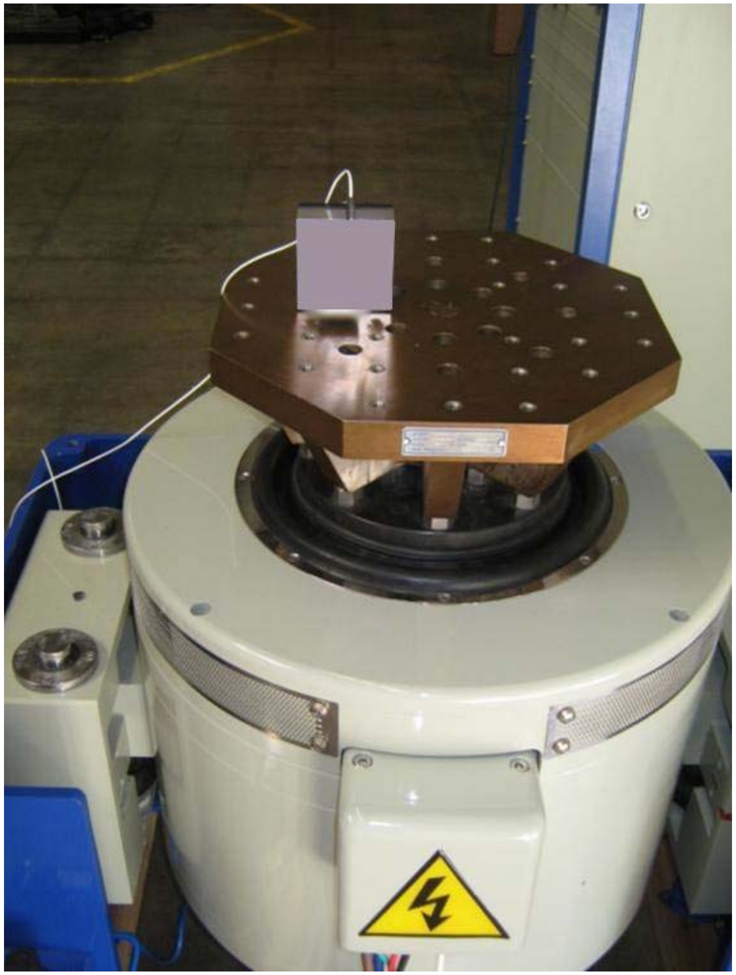
Electromagnetic shaker
Vibration testing and 1-DOF dynamics

Dynamics Solutions Shaker, DS-1300
1300 lbf, 2″ stroke
21 kVA power
Controlled drive: random, sine shock
Bandwidth 2 to 2500 Hz
V_{max} = 55 in/s
$a_{max} = 50g$

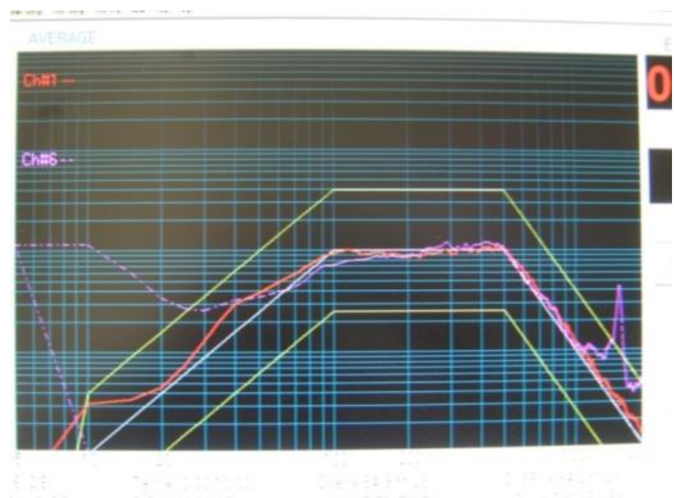
Potential risks
- residual B ≈ 10 G
- acoustical coupling

Technology validation

Acceleration testing of components & subsystems



Acceleration testing
• 5 Hz – 2 kHz
• up to 50*g* swept sine
• detect resonances
• test and improve mounts



Stewart motion table, 6 DOF (hexapod)

MaxCue 600

Specs:

- actuator thrust 13 kN (2,900 lbf)
- a_{max} = 0.6 to 2*g*
- $V_{max} \approx 0.6$ m/s
- displacement range 0.5 to 0.9 m
- rotation range ≈ ±35°
- rotation rate max ≈ 50 °/s
- Bandwidth DC- 25 Hz

- Status – installed & working

Thanks to NGA, T. Johnson for loan of GFE

Technology Vision

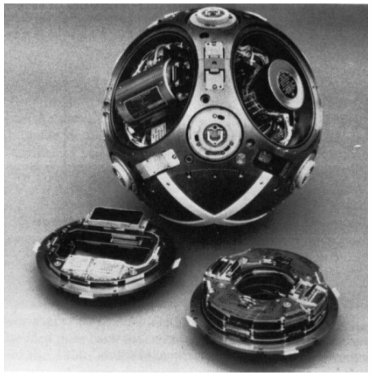
Target Applications

Gravimetric
- Geodesy/Earthquake prediction
- Oil/mineral/resource management
- Gravity anomaly detection

Low cost, compact, navigation grade IMU
- Autonomous vehicle navigation

Gravity compensated IMU (grav grad/gyro)
- GPS-free high accuracy navigation

Existing high accuracy inertial technology:



www.fas.org

19,000 parts
1970 technology.
2001: 652 units ordered.
Source: www.fas.org

Honeywell
H1900 IMU

Target Specs

- Inertial+ grade IMU
  - < 10 liters
  - < 10 m/hr drift
  - < 100 Watts
  - Gravity compensated
- Navigation grade IMU
  - < 0.1 liters
  - < 1 Watt
  - Low-cost ($1K ?)

Recent scientific questions

Can sensitivity be improved with new classes of atom optics?

- Large momentum transfer atom optics

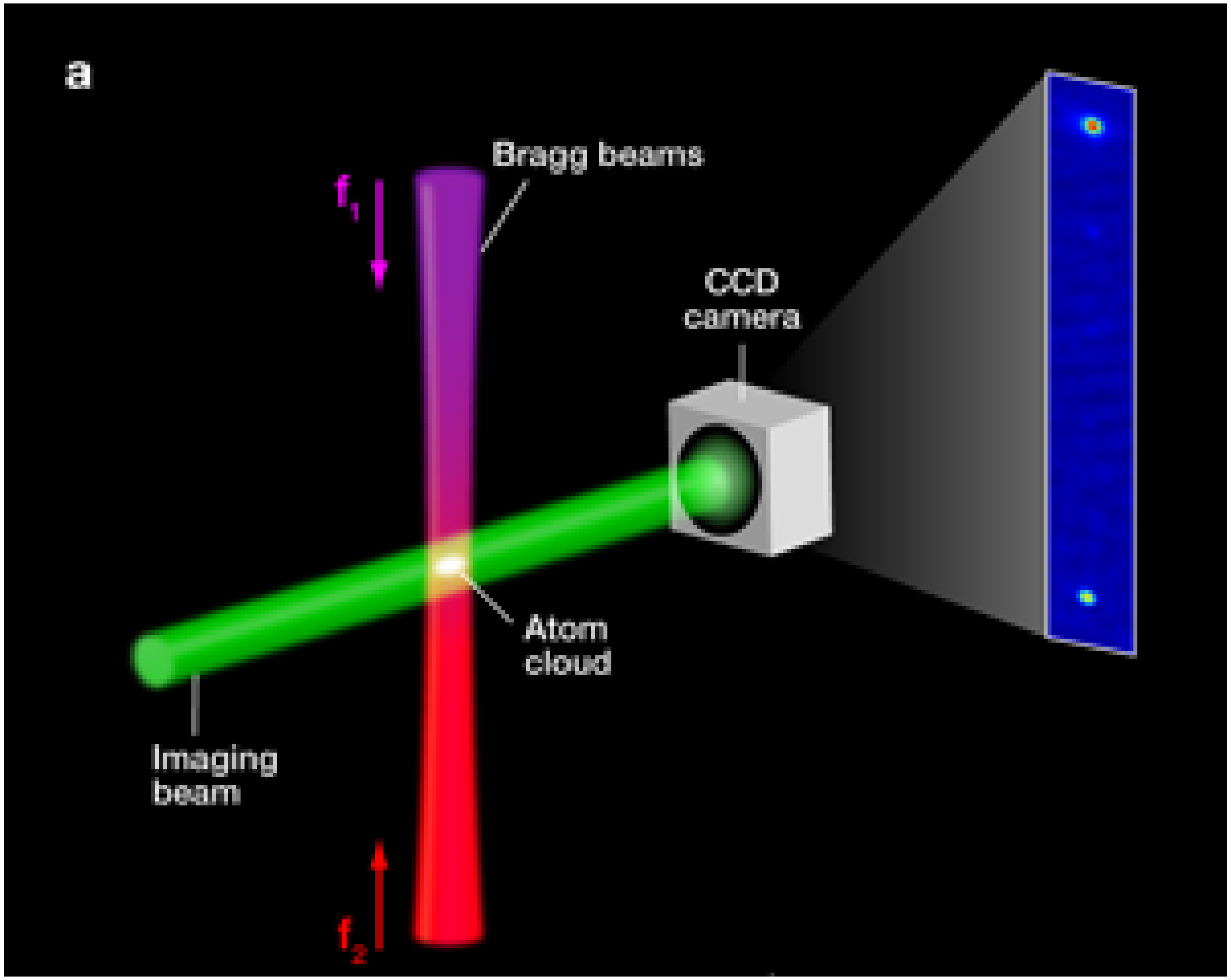
Can precision atom interferometric methods be extended to massive particles?

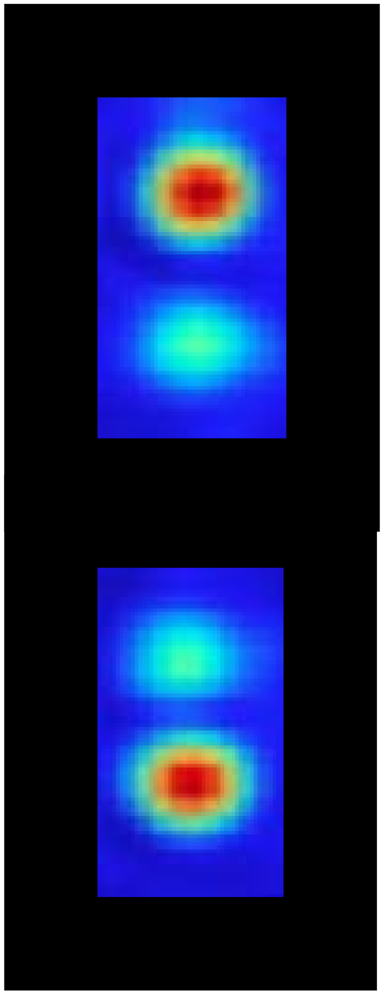
- sensitivity scales with particle mass

Can quantum information science approaches be used to improve interferometer sensitivity?

- sub-shot-noise interferometry
- 10x – 100x sensitivity improvement

Large momentum transfer atom optics





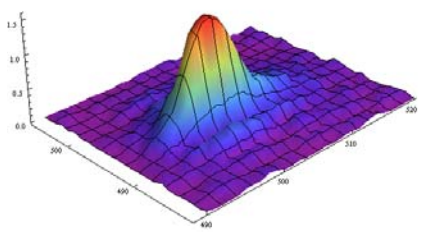
200 photon recoil atom optics

Chiow, PRL, 2011

Science

Gravitational physics

- Equivalence Principle (^{85}Rb vs ^{87}Rb, $\delta g \sim 10^{-15}$ g in 1 month)
- Gravity-wave detection
- Post-Newtonian gravity, tests of GR
- Tests of the inverse square law
- Dark matter/energy signatures?



Evaporatively cooled atom source

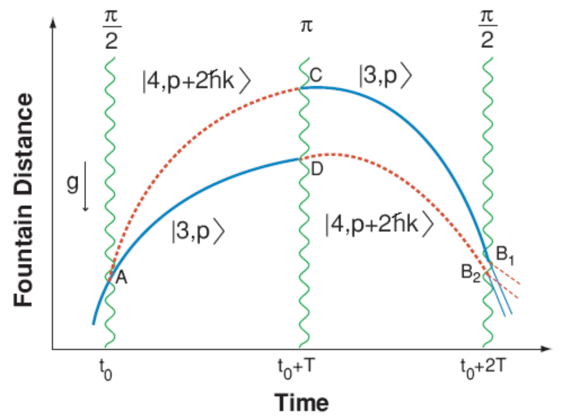
10 m drop tower

Physical sensitivity limits (10 m apparatus)

Quantum limited accelerometer resolution: ~ 7×10^{-20} g

Assumptions:

1) Wavepackets (Rb) separated by z = 10 m, for T = 1 sec. For 1 g acceleration: $\Delta\phi \sim mgzT/\hbar \sim 1.3 \times 10^{11}$ rad
2) Signal-to-noise for read-out: SNR ~ 10^5:1 per second.
3) Resolution to changes in g per shot: $\delta g \sim 1/(\Delta\phi\ SNR) \sim 7 \times 10^{-17}$ g
4) 10^6 seconds data collection



How do we exploit this sensitivity for science and technology?

Quantum Metrology: Sub-shot noise detection

Atom shot noise limits sensor performance.

Recently evolving ideas in quantum information science have provided a road-map to exploit exotic quantum states to significantly enhance sensor performance.

- Sensor noise scales as 1/N where N is the number of particles
- "Heisenberg" limit
- Shot-noise ~ $1/N^{1/2}$ limits existing sensors

Challenges:

- Demonstrate basic methods in laboratory
- Begin to address engineering tasks for realistic sensors

Impact of successful implementation for practical position/time sensors could be substantial. Possible 10x – 100x reduction in sensor noise.
Enables crucial trades for sensitivity, size and bandwidth.

Conclusion

- Numerous cold atom sensors applications
  - Can trade-off accuracy vs bandwidth
  - High performance navigation to lower performance tactical

Image credit (Wikipedia):
Steve Jurvetson

- Strong demand for GPS independence
- Excellent performance demonstrated in lab
- Planning for field testing underway